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COASTAL ZONE MANAGEMENT SUBGROUP
RESPONSE STRATEGIES WORKING GROUP
INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

GLOBAL CLIMATE CHANGE AND THE RISING CHALLENGE OF THE SEA

CAMBIO CLIMATICO GLOBAL Y EL RETO DEL INCREMENTO DEL NIVEL DEL MAR

PROCEEDINGS OF THE INTERNATIONAL WORKSHOP
HELD ON MARGARITA ISLAND, VENEZUELA
Hosted by the Venezuelan Ministry of Environment and Renewable Natural Resources
MARCH 9-13, 1992

MEMORIAS DEL TALLER INTERNACIONAL REALIZADO
EN LA ISLA DE MARGARITA, VENEZUELA
Auspiciado por el Ministerio del Ambiente y de los Recursos Naturales Renovables de Venezuela
9-13 DE MARZO, 1992

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TALLER INTERNACIONAL
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These papers were prepared and presented by the workshop participants. Although the workshop was conducted under the auspices of the Intergovernmental Panel on Climate Change, the IPCC co-sponsorship does not imply IPCC endorsement or approval of these papers.

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Ing. Martha Perdomo
Co-Chair—Coastal Zone Management Subgroup
Co-Presidente-
Subgroup de Manejo de Zonas Coasteras

Dr. Pier Vellinga
Co-Chair—Coastal Zone Management Subgroup
Co-Presidente-
Subgroup de Manejo de Zonas Coasteras

CONTENTS

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1992
Copy 2

OVERVIEW AND SUMMARY

The Rising Challenge of the Sea 3
Findings and Recommendations 4

CASE STUDIES OF SMALL ISLANDS

Assessment of the Vulnerability of Coastal Areas in Antigua and Nevis to Sea Level Rise
Gillian Cambers 11

Preliminary Assessment of the Vulnerability of Kiribati to Accelerated Sea Level Rise
Colin D. Woodroffe 29

Assessment of the Vulnerability of Majuro Atoll to Sea Level Rise
M. Crawford, P. Holthus, C. Makroro, E. Nakasaki, and S. Sullivan 49

Assessment of the Vulnerability of Mauritius to Sea Level Rise
Vasantt K. Jogoo 107

Assessment of the Vulnerability of the Kingdom of Tonga to Sea Level Rise
Netatua P. Fifita, Nobuo Mimura, and Nobuyuki Hori 119

CASE STUDIES OF DELTAS

Assessment of the Vulnerability of Bangladesh to Sea Level Rise
Amjad Hossain Khan, Saleemul Huq, A. Atiq Rahman, M. Shahidullah, A. Haque, Syed Ali Naqi, Mujibur Rahman, Saleh Ahmed, Syed Iqbal Ali, Mohammad Youssouf Ali, Mohiuddin Ahmed, Yusuf Islam, and Feroze Mollick 143

The Impacts of Sea Level Rise on China's Coastal Areas
Xu Qiwang, Lu Chunhua, Zhang Yushu, and Niu Bin 157

The Impacts of Sea Level Rise in the Year 2100 on Bohai Bay, the Huanghe River Delta, and Laizhou Bay
Liu Zhenxia, Xia Dongxing, Wang Delin, Li Xuan, Wu Sangyun, and Li Fulin 165

Assessment of the Vulnerability of Egypt to Sea Level Rise
A.A. Khafagy, C.H. Hulsbergen, and G. Baarse 183

Assessment of the Vulnerability of Orissa and West Bengal, India, to Sea Level Rise
V. Asthana, S. Surendra, and S. Venkatesan 197

Assessment of the Vulnerability of The Netherlands to Sea Level Rise
G. Baarse, E.B. Peerbolte, and L. Bijlsma 211

The Impacts of Sea Level Rise on the Coastline of Nigeria
Larry F. Awosika, Gregory T. French, Robert J. Nicholls, and C.E. Ibe 237

CASE STUDIES OF CONTINENTS AND LARGE ISLANDS

The Impacts of Sea Level Rise on Argentina's Coastline
Gerardo M.E. Perillo and Maria Cintia Piccolo 263

The Impacts of Sea Level Rise on the Coast of Argentina
Enrique J. Schnack, Karen Clemens Dennis, Felix H. Mouzo, and Robert J. Nicholls 275

Assessment of the Vulnerability of Geographe Bay, Australia, to Sea Level Rise
Robert Kay, Ian Eliot, and Geoff Klem 293

The Impacts of Sea Level Rise on Rochefort sur Mer, France
Christian Auger 317

Impacts of Sea Level Rise on Japanese Coastal Zones and Response Strategies
Nobuo Mimura, Masahiko Isobe, and Yasushi Hosakawa 329

Río Lagartos, Yucatán, México Special Biosphere Reserve: A Case Study
Gustavo de la Cruz Agüero, Gerardo Gold Bouchot, Víctor Alcántar Cárdenas, and Juan José Durán Nájera 351

Efectos del Incremento del Nivel del Mar en la Costa Peruana por Influencia del Calentamiento Global (The Impacts of Sea Level Rise on the Peruvian Coast Caused by Global Warming)
César doe Carmen de la Torre and Gustavo Laos Cruzado 359

The Rising Challenge of the Sea for Poland
R.B. Zeidler and G. Toms 373

The Impacts of Sea Level Rise on the Coastline of Senegal
Isabelle Niang, Karen Clemens Dennis, and Robert J. Nicholls 407

The Impacts of Sea Level Rise on the Coastline of Uruguay
Claudio R. Volonté and Robert J. Nicholls 427

The Impacts of Sea Level Rise on the Coastline of Venezuela
José Arismendi and Claudio R. Volonté 451

Gestión de Costas en Venezuela (Coastal Management in Venezuela)
Ernesto Díaz V. 473

INTERGOVERNMENTAL STUDIES

INTERGOVERNMENTAL OCEANOGRAPHIC COMMISSION

Activities and Plans of the IOC Related to Coastal Zone Management and Sea Level Rise
George A. Maul 483

Global Climate Change and Coastal Land Loss: Management and Decision Making in Support of Sustainable Development Within the Caribbean and Adjacent Regions
Georges Vernette 487

UNITED NATIONS ENVIRONMENT PROGRAMME

Climate Impact Studies in Low-Lying Coastal Areas and Small Islands of UNEP's Regional Seas Programme
Makram A. Gerges and Mahmoud Kh. El-Sayed 525

Implications of Expected Climate Change in the Mediterranean Region
L. Jeftic 539

Climate Change and Sea Level Rise in the Wider Caribbean and Adjacent Seas
Beverly A. Miller 561

WORLD METEOROLOGICAL ORGANIZATION

The Challenge of Sea Level Rise for the World Meteorological Organization
G.O.P. Obasi 565

OTHER RELATED STUDIES

Quantification of Resources at Risk to Sea Level Rise in Developing Countries
Neal Devine and Norbert P. Psuty 571

The Impacts of Sea Level Rise on Coastal Areas: Some Global Results
F.M.J. Hoozemans, M. Marchand, H. Pennekamp, M. Stive, R. Misdorp, and L. Bijlsma 607

The Insurance Mechanism: An Industry Comment
Andrew F. Dlugolecki 623

Expected Responses of Caribbean Coral Reefs to Disturbances Caused by Sea Level Rise
Vance P. Vicente 635

Impacts of Sea Level Rise on Pacific Island Mangrove Swamps
Joanna C. Ellison 641

Probability Distribution of Future Sea Level Rise
James G. Titus and Vijay Narayanan 659

History of Tropical Cyclones in the Caribbean: 1886–1986
Calvin R. Gray 677

OVERVIEW & SUMMARY

OVERVIEW AND SUMMARY

THE RISING CHALLENGE OF THE SEA

Where the sea meets the shore, the forces of nature have always challenged human activities. Human activities are exacerbating the vulnerability of coastal areas to sea level rise. Many coastal areas, as a result of human activities, already face increased erosion, flooding, loss of wetlands, and salinity of surface and ground water. Coral and sand mining, deforestation of mangroves, and construction of dams and levees all thwart the natural processes that would otherwise mitigate the erosion, flooding, and other potential impacts caused by an acceleration in sea level rise.

Moreover, global population is expanding at an unprecedented pace. The majority of this growth is expected to take place in heavily populated coastal areas, particularly in developing countries. At present, 100-200 million people live in very low-lying areas potentially subject to annual flooding. This projected population growth would increase the number of people vulnerable to sea level rise. Human-induced climate change and the resulting rise in sea level would significantly increase the stresses on coastal resources—particularly for small island and deltaic nations.

An intergovernmental Framework Convention on Climate Change has been negotiated (May 1992) as a first step toward controlling global activities responsible for greenhouse gas emissions. Even if these emissions are controlled, atmospheric concentrations of greenhouse gases would still increase for decades, and thus accelerate sea level rise during the next century. Therefore, nations will have to adapt to sea level rise and other coastal impacts of global climate change. Although most of the consequences are several decades away, many of the responses require equally long lead times. Moreover, the most vulnerable areas could experience the consequences much sooner. A successful adaptation to sea level rise will require unprecedented foresight and substantial changes in how nations manage their coastal environments. Ultimately, they should strive to protect coastal resources while encouraging their sustainable use.

This report presents the proceedings of "The Rising Challenge of the Sea," the third international workshop of the Coastal Zone Management Subgroup (CZMS) of the Intergovernmental Panel on Climate Change (IPCC). An Executive Summary Report was produced in May 1992. Held on Margarita Island in Venezuela, March 9 to 13, 1992, the workshop was attended by 114 people representing 33 countries and 10 regional and international organizations. Its purpose was to present the status of 25 case studies assessing vulnerability to sea level rise. Because an accelerated rise in sea level presents new issues, analyzes and experiences should be shared globally. Toward that end, these studies provided supporting material for the CZMS contribution to the 1992 Supplement to the IPCC 1990 First Assessment Report.

In addition, these proceedings contain information on the need to adapt to an acceleration in sea level rise, which is relevant to the Framework Convention on Climate Change. The convention includes a provision (Article 4, paragraph E) that calls for parties to develop national programs for responding to climate change, with a specific reference to developing coastal zone management plans.

The information in this report is also relevant for international follow-up to the United Nations Conference on Environment and Development (UNCED). The UNCED (June 1992) was held to promote the integration of environmental protection with sustainable development. The UNCED ocean and coastal areas component (Chapter 17 of Agenda 21, the UNCED Action Plan) was under discussion by the UNCED Preparatory Committee at its fourth and final meeting during the same week as the Margarita Island Workshop. The workshop participants noted that the text before the UNCED Preparatory Committee contained a proposal calling for the development of national coastal zone management programs and for international cooperation in the preparation of national guidelines for coastal zone management, including a global conference to exchange experience in the field.

Participants at the workshop noted that these proposals were consistent with the IPCC recommendation that nations develop and, where possible, implement coastal zone management plans to reduce vulnerability to sea level rise before the year 2000. A consideration of accelerated sea level rise can help to establish priorities for coastal zone management. The workshop participants noted that the Framework Convention on Climate Change and the UNCED Agenda 21 can facilitate national and international responses to meet this coastal challenge.

Discussions at the workshop included another proposal proposed during the negotiations of the Framework Convention on Climate Change on insurance for low-lying developing countries vulnerable to sea level rise, particularly small islands. The proposal would have provided financial resources for areas vulnerable to sea level rise. During the discussions, scientific and technical issues related to the proposal were raised. These included the difficulty both in estimating the portion of damages attributable to anthropogenically induced climate change and in quantifying the damages, the need for the beneficiaries to take prudent precautions to avert damages, and the distinctions from traditional forms of insurance.

The CZMS remains ready and willing to provide objective scientific and technical information to assist with further analyzes of strategies for meeting the challenge of rising sea level within the context of integrated coastal zone management.

FINDINGS AND RECOMMENDATIONS

The following findings were derived from the IPCC/CZMS preliminary case studies presented in 1992 at the Margarita Island Workshop and are excerpted from the workshop Executive Summary (*Global Climate Change and the Rising Challenge of the Sea, May 1992*). They further elaborate and expand upon the findings in the 1990 IPCC Report that were derived from the IPCC/CZMS Workshops held in Miami (1989) and Perth (1990).

FINDINGS

1. **The urgency of implementing strategies for adapting to sea level rise is greater than previously thought because of both the long lead times needed for planning, and factors not related to climate change.**

In many parts of the world, the natural systems that provide protection against the sea are being degraded by development activities through mining for sand and coral, cutting mangroves, damming and confining the flows of rivers, and filling wetlands. Every year that countries postpone addressing these issues, they continue to increase their vulnerability to sea level rise.

Moreover, environmentally sound responses have lead times of several decades and longer. Thus, even though the effects of accelerating sea level rise are still decades away, now is the time to take action.

2. **Globally, a rise in sea level of one meter could double the number of people vulnerable to annual storm surges.**

Currently, between 100 and 200 million people are estimated to live below the annual storm surge level. About 20 percent of this population experiences flooding annually. If the sea rises one meter above the current mean sea level, and coastal defense systems are not fortified, then the number of people subject to annual flooding would increase by about 50 percent. Extrapolating the existing population growth rates to the year 2020 would double the number of people subject to annual flooding.

3. **The total cost for adapting to a one-meter rise in sea level will be greater than the cost for basic protection measures.**

The 1990 IPCC Report estimated the cost of basic protection measures for a one-meter rise in sea level to be about $500 billion over the next 100 years. The 1990 estimate reflected only the marginal or added costs and was not discounted. As indicated in the 1990 Report, that analysis by design did not include all costs, and thus the overall costs would be higher. Specifically, the 1990 estimate did not include costs necessary to meet present coastal defense needs, the values of the unprotected dry land or ecosystems that would be lost, or the costs of responding to salt-water intrusion or the impacts of increased storm frequency.

When viewed as a group, the preliminary case studies suggest that these additional costs could significantly increase the estimate of total costs of adaptation. The case studies of Nigeria, Senegal, Argentina, Uruguay, and Venezuela only considered basic protection measures, and give estimates similar to those in the 1990 Report. By contrast, the more comprehensive studies of Japan, the United States, and the Netherlands reported costs at least three times higher than the previous estimate.

4. **For many coastal states, particularly small island developing countries, the costs of adapting to a rise in sea level could be large compared to the size of their economies.**

Each of the case studies presented by small island countries estimated that the annual costs of protection for a 1-meter rise in sea level over the next century would be greater than 1 percent of their current gross domestic product (GDP). Some estimated annual costs would be greater than 3 percent of their GDP. Several studies in continental developing countries estimated that they would also have costs that are large relative to their current GDPs.

5. **The potential global impact of accelerated sea level rise on coastal wetlands could be substantial.**

Coastal wetlands are critical to the life cycles of species that make up two-thirds of the world's marine fisheries. Migratory birds and other species depend on them for habitat. Each of the case studies indicated that, without adaptive strategies, a one-meter rise in sea level over the next century could result in a significant net loss of coastal wetlands. In coastal wetland areas that have small tidal ranges and rapid subsidence, significant net losses of wetlands could result even with a 50-cm rise in sea level. Coastal protection measures will increase the loss of coastal wetlands, underlining the limits of adaptation.

6. **Common methodologies provide a valuable tool for coastal states to use in assessing their vulnerability to sea level rise and for coastal planning.**

The case studies have demonstrated the value to coastal states of assessing their vulnerability to sea level rise. Developing and developed nations alike found the CZMS common methodology a useful tool in conducting such assessments. For example, by applying the common methodology, many of the case study nations were able to both identify areas vulnerable to sea level rise and evaluate various response strategies. Even though some developing countries did not have all the data required by the methodology to conduct a comprehensive vulnerability assessment, they found the application of the methodology through a case study to be a valuable exercise. Common methodologies also stimulate communication and exchange of data, methods, and technology among countries at all levels—policy, technical, scientific, and academic. Moreover, such methodologies appear to be efficient because they avoid duplication of effort.

7. **Response measures to reduce vulnerability to sea level rise should be implemented through coastal zone management planning.**

The case studies demonstrated the importance of taking actions to reduce vulnerability to sea level rise within the context of coastal management planning. Such planning allows coastal states to take into account in an integrated manner the many diverse interests and uses of their coastal resources. The implementation of response strategies will have implications for almost every aspect of coastal activities; therefore, they need to be considered comprehensively to achieve optimal results.

RECOMMENDATIONS FOR FUTURE ACTIVITIES

In light of the above findings, the following activities are recommended for future work, with an emphasis on enhanced international cooperation.

1. **Coastal states should assess their vulnerability to an accelerated rise in sea level and to other potential coastal impacts of global climate change.**

Many of the case studies on vulnerability to sea level rise presented at the Margarita Island Workshop were in the preliminary stages and require additional effort to be completed comprehensively. These case studies should be completed and expanded to include other potential coastal impacts of global climate change. Coastal states that have not done so should assess their vulnerability by using the CZMS common methodology, tailoring it to their individual circumstances.

2. **Coastal states that have conducted vulnerability assessments should begin the process of planning for appropriate response strategies.**

The experience of the CZMS members indicates that the process of planning and implementing responses to sea level rise requires a long lead time. If coastal states are to effectively plan for and successfully implement responses, they should initiate the process now.

3. **The CZMS should continue to facilitate and build on its information network.**

The CZMS network can assist coastal states with access to the information, data, and procedures that they need to conduct vulnerability assessments and to develop coastal management plans. The CZMS should continue to disseminate, through this network, information about the case studies and other relevant activities. This effort should include information on the location of and access to relevant data bases and training opportunities.

4. **Cooperation in the development of national guidelines for coastal zone management is needed.**

Both the 1990 IPCC Report and the 1992 Supplement recommended that by the year 2000, coastal states should develop, and where possible implement, comprehensive coastal management programs to reduce their vulnerability to sea level rise. To facilitate implementation of this recommendation, the CZMS should work with relevant international organizations to develop national guidelines for coastal zone management.

5. **The CZMS should cooperate with the other IPCC subgroups to prepare an integrated assessment related to sea level rise and other coastal impacts of global climate change.**

Several areas of investigation identified as priorities for future CZMS work require closer collaboration with other IPCC subgroups. For example, the CZMS should work in cooperation with other experts to (1) enhance local and regional predictions of sea level rise and severe storms and (2) evaluate measures for responding to the impacts of sea level rise on natural defense systems, such as coral reefs, mangroves, and sea grasses.

6. **Support for and cooperation with international organizations that are coordinating relevant data sets and implementing systematic observation and monitoring networks should be increased.**

Data that are essential for the effective use of the common methodology are not available for many coastal states. Data on sea level, severe storms, land use and capability, topography, bathymetry, natural vegetation distribution, sediment type and rates of deposition, elevation, population distribution, etc., either do not exist for these coastal states or are not stored in any central, retrievable system.

Several international organizations, including the Intergovernmental Oceanographic Commission (IOC), the United Nations Environment Programme (UNEP), and the World Meteorological Organization (WMO), are coordinating the development and implementation of global monitoring systems to address these data requirements. However, there are still large gaps, and addressing these deficiencies will require additional support. Moreover, the accessibility of data is poor, underlining the need for facilitating data and information exchange, as mentioned under Recommendation 3.

7. **Vulnerability to sea level rise and the need for coastal zone management are important factors that should be considered in decisions on planning and funding of coastal development, including those by international financial and development agencies.**

Many projects, including those funded by international financial institutions and development agencies, have the potential to increase or decrease the eventual vulnerability of coastal nations to sea level rise. These projects include dams, flood protection works, and other kinds of sectoral coastal development. To avoid increasing vulnerability to sea level rise, these concerns should be factored into decision making.

The issues of sea level rise and coastal zone management are inextricably linked to decisions regarding sustainable coastal development. However, many coastal countries lack the human, financial, and institutional resources necessary for integrating these activities. The required levels of training, technical assistance, and public education often necessitate outside assistance to facilitate their development. Coastal states can bring these issues to the attention of such international institutions as the World Bank, Regional Development Banks (Inter-American, Asian, African, etc.), and the United Nations Development Programme.

The findings and recommendations of this report complement those of the 1990 IPCC Report and the 1992 Supplement. They should be viewed in conjunction with each other.

CASE STUDIES OF SMALL ISLANDS

ASSESSMENT OF THE VULNERABILITY OF COASTAL AREAS IN ANTIGUA AND NEVIS TO SEA LEVEL RISE

Gillian Cambers
Conservation & Fisheries Department
Tortola, British Virgin Islands, West Indies

ABSTRACT

This paper has used the IPCC Common Methodology to assess the vulnerability of coastal areas to sea level rise for the Organization of Eastern States (OECS) in general, and for Antigua and Nevis, in particular. These two islands were selected because they are heavily dependent on coastal resources for their major industry—tourism—yet they differ in their approach to managing their coastal resources.

The climate factors considered are accelerated rises in sea level of 0.3 and 1.0 meters by the year 2100. In addition, flooding due to increased frequency and magnitude of hurricanes is considered. Saltwater intrusion, although potentially important, is not considered due to an absence of data.

The major impacts on each island are a loss of urban land, construction sand, and recreational (beach) area. The major potential responses are evaluated: do nothing, retreat, accommodate, and protect. While it is recognized that most islands will "do something," retreat is not expected to be a favored response due to the high cost of land, the shortage of land, and the constraints imposed by other infrastructure. Accommodation is a feasible alternative for new development when combined with coastal setback policies. To protect is likely to be the most favored response, although at present solid structures are favored.

Protection strategies are estimated for each sea level rise scenario and are expected to be between 10 and 100 times existing expenditures on sea defenses. The full vulnerability analysis could not be completed, due to an absence of detailed socioeconomic data in the coastal zones. However, it was recognized that since 75–78 percent of the lowland beach coasts of these two islands is undeveloped, they have an opportunity to accommodate future coastal setbacks, adaptive building techniques, etc. However, their present institutional, organizational, and financial structures are inadequate to develop the necessary responses. Nevis has comprehensive coastal legislation with adequate zoning guidelines; however, these have yet to be implemented and tested. Antigua, like the other islands of the OECS, does not have the necessary coastal legislation.

Climate change and sea level rise issues are often viewed by the small islands of the OECS as being too overwhelming and too remote. Therefore, projects dealing with sea level rise should be combined with ongoing programs dealing with such areas as coastal zone management, beach monitoring, and disaster preparedness. The islands of the OECS will require considerable external assistance to develop and implement the necessary strategies to respond to accelerated sea level rise.

INTRODUCTION

Within the Eastern Caribbean Islands, the subject of climate change and, in particular, sea level rise has received some consideration at the technical and professional levels, but little attention at the political and general public levels. A recent study by Bass and Cambers (1991) recommended linking the issues raised by climate change to existing problems of economic consequence, such as hurricanes, beach and soil erosion, and flooding. Otherwise the issues might be viewed as too remote and too overwhelming to deal with using limited resources. To date, most of the work relating to climate change in the Eastern Caribbean Islands has been of a qualitative, general nature.

This paper represents the results of a short-term desk study that aimed to provide a first-order assessment of vulnerability to sea level rise for two Eastern Caribbean Islands. It recognizes that further work is required, especially on the quantitative data.

The smaller English-speaking islands of the Eastern Caribbean consist of nine countries—Anguilla, Antigua-Barbuda, British Virgin Islands, Dominica, Grenada, Montserrat, St. Kitts-Nevis, St. Lucia, and St. Vincent and the Grenadines (Figure 1). Their areas range from 90 to 750 km^2, and their populations vary from 7,000 to 120,000 persons. All these countries, except Anguilla, belong to the Organization of Eastern Caribbean States (OECS). Anguilla, British Virgin Islands, and Montserrat are British-dependent territories; the other six countries are independent nations. General impacts and responses to sea level rise in these countries have previously been described by Cambers (1991a).

THE STUDY AREA

Two islands have been selected for this present study: Antigua, which is the main island in the nation Antigua-Barbuda, and Nevis, which is the smaller island in the nation St. Kitts-Nevis. These two islands were selected because they are both heavily dependent on their coastal resources for the main industry—tourism—yet they differ in the extent of their coastal development. The coast of Antigua is more densely developed for tourism than that of Nevis. The two islands also manage their coastal resources differently. Thus, they provide interesting contrasts within the context of the OECS, particularly with regard to responses to sea level rise.

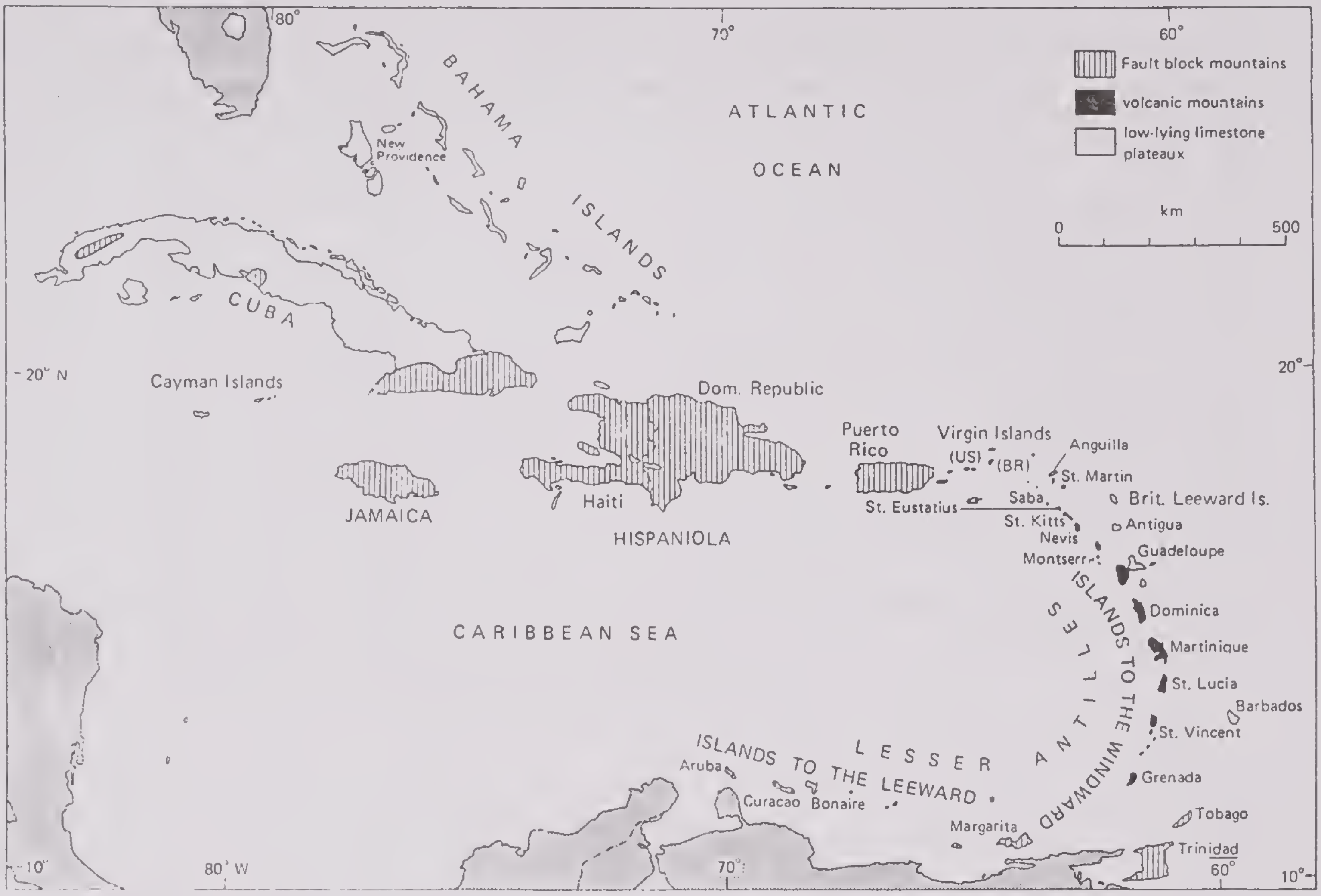
NATURAL CHARACTERISTICS

Table 1 details the characteristics of the natural systems for the two islands. About 21 percent of Antigua's 193-km coast consists of sandy beaches, 11 percent, mangroves and wetlands, and 68 percent hard-rock cliffs. In addition, 6 percent of the coastline is protected with either revetments or bulkheaded reclamations.

The 40-km coast of Nevis is much less indented. About 25 percent is composed of sandy beaches, and 75 percent is composed of hard-rock cliffs. Coastal mangroves and wetlands represent 2 percent of the Nevis coastline.

On both islands, coral reefs are an important resource—for fisheries, beach protection, source of beach sand, habitat, and tourism. The linear length of coral reefs in each island is shown in Table 1.

FIGURE 1. LOCATION MAP OF THE EASTERN CARIBBEAN ISLANDS



Source: Blume (1976).

SOCIOECONOMIC CHARACTERISTICS

Along with the other Eastern Caribbean Islands, Antigua and Nevis have a high population density (Table 2). In Antigua, over 50 percent of the population is concentrated in the coastal zone. For Nevis, examination of the topographic map indicates that the percentage is less. Quantitative estimates are not at present available.

In both countries, agriculture contributes only a small percentage to the gross domestic product (GDP). The figure given in Table 2 for Nevis is probably on the high side, since it includes St. Kitts, where the cultivation of sugarcane is still an important industry. In addition, there is very little agriculture in the coastal zone because of high salinity and sea-blast effect. There is some coconut cultivation in Nevis in the coastal zone, and some livestock grazing in Antigua.

Tourism is a rapidly growing industry in the Eastern Caribbean. During the 1980's, the numbers of arrivals grew steadily, despite some short-term fluctuations due to worldwide recession and other factors. Table 2 shows clearly how important tourism is as a percentage of the GDP. In Antigua, 1982 tourism receipts accounted for 34 percent of the GDP, and in Nevis, for 16 percent. The percentage is likely to be higher in 1992. In Antigua, tourism receipts exceed visible exports (UN ECLAC, 1985).

TABLE 1. NATURAL CHARACTERISTICS OF ANTIGUA AND NEVIS

Coastal Characteristics	Antigua	Nevis
Coastline length (km)	193	40
Length of sand beaches	41	10
Length of mangroves/wetlands (km)	21	1
Length of hard cliff line (km)	131	29
Linear length of coral reefs (km)	76	45
Man-made coastline:		
•Length of reclamations (km)	5.5	0
•Length of sea walls/revetments (km)	5.5	1
•Length of coastline with groins (km)	0	0.5
Tidal range (m)	0.3	0.3
Wave climate:		
•Windward coasts Hs (m) (90% exceedance)	1.9	1.9
•Deep-water swell Hs (m) 10/season	1.2	1.2
•Deep-water swell Hs (m) 1/season	3.7	3.7
•Hurricane Hs (m) (wind speed 204 km/hr)	8.2	8.2
Flood frequency	1 in 5 yrs	1 in 5 yrs

Table 2 also shows that in Antigua, 81 percent of the hotels are located in the coastal zone, while in Nevis 54 percent are on the coast. (This category excludes guest houses and holiday apartments.) In the past, Nevis has concentrated its tourist accommodation in "The Inns of Nevis," most of which were located inland on the lower slopes of Nevis Peak. However, recently this has started to change with the opening of a 200-room hotel on the coast.

ANALYTICAL APPROACH

SCOPE OF STUDY

The study area consists of the entire coastal area for each island. The landward limit of the study area is the 15-meter (50-foot) contour, which is the lowest one shown on the 1:50,000 topographic map for Antigua and the 1:25,000 topographic map for Nevis. These two map scales formed the basis of the quantitative data used in this study. Larger-scale maps do exist with smaller contour intervals. Thus, in later, more refined studies, it may be possible to use the 3- and 6-meter (10- and 20-foot) contours.

The seaward limit of the coastal area in this study is the 18-meter (60-foot) drop-off. This is 22 km offshore in Antigua and 2 km offshore in Nevis.

CLIMATE FACTORS

The main climate factor to be considered will be the effects of sea level rise. However, other factors are also important in the Eastern Caribbean, especially the magnitude and frequency of hurricanes. The existing frequency of hurricanes, based on statistics quoted in De Souza (1966) and Admiralty Pilot (1969), is shown in Table 3.

TABLE 2. SOCIOECONOMIC CHARACTERISTICS OF ANTIGUA AND NEVIS

Socioeconomic Characteristic	**Antigua**	**Nevis**
Population	77,093	10,000 (E)
Population density (persons/km^2)	175	108
GDP per capita (1987 EC$)	8,103	5,283*
GDP growth 1986/1987 (%)	16.29	9.54
Percentages of 1987 GDP^:		
Agriculture	4.68	9.44*
Manufacturing	3.69	14.38
Construction	11.71	7.75
Hotels & restaurants	15.38	9.35
Government services	15.54	19.20
Other	49.00	39.88
Balance of visible trade (thousands of EC$)	(705,786)	(141,358)
Stayover visitors in 1987	173,233	66,450
Cruise ship visitors in 1987	153,308	31,438
Total number of hotels	36	11
Number of hotels in coastal zone	29	6

(E)= Estimate.
* Figures refer to nation of St. Kitts-Nevis.
^ GDP by economic activity at factor cost (current prices).

TABLE 3. EXISTING AND PROJECTED FREQUENCY OF HURRICANES IN ANTIGUA AND NEVIS

	Antigua	**Nevis**
Frequency of hurricane center passing within 160 km (1901-1964)	1 in 5 yrs	1 in 5 yrs
Projected frequency of hurricane center passing within 160 km for year 2050	1 in 3.5 yrs	1 in 3.5 yrs
Frequency of hurricane center passing over country (1901-1964)	1 in 21 yrs	1 in 31 yrs
Projected frequency of hurricane center passing over country for year 2050	1 in 10 yrs	1 in 15 yrs

Note: Projected figures are purely estimates, in the absence of a detailed climate change assessment for the Eastern Caribbean region.

It is difficult to isolate other climate parameters, such as temperature and rainfall changes, when dealing with the physical and socioeconomic impacts of sea level rise. The Eastern Caribbean Islands are heavily dependent on tourism. Changes in temperature and humidity—however small—could affect comfort levels for tourists. This, in turn, could undermine the dominance of tourism, thereby influencing how the islands respond to sea level rise. As will be seen in this study, the nature of the islands' response to sea level rise is heavily influenced by the importance of tourism and the need to conserve beaches as an important part of the tourism product. However, for this study, it has been assumed that tourism will remain the dominant industry, and changes in other climate factors have been neglected.

ACCELERATED SEA LEVEL RISE SCENARIOS

The sea level rise scenarios considered in this study are :

- Base case: no accelerated sea level rise.
- A 0.3-meter rise by 2100.
- A 1.0-meter rise by 2100.

Within Antigua and Nevis and the entire OECS, there are no permanently established tidal gauges that would provide a record of short- and/or long-term sea level changes in the region.

IMPACTS OF SEA LEVEL RISE

The major impacts of sea level rise will be :

1. Changes in the shoreline, erosion, or accretion.
2. Raised water levels in ponds, lagoons, inland seas, and wetlands.
3. Saltwater intrusion.

The major impacts dealt with in this study are the changes in the shoreline. Raised water levels will have a greater impact on Antigua than on Nevis, because Antigua has a larger percentage of wetlands. On the other hand, shoreline erosion on Nevis is likely to be severe.

There are no data on the impacts of saltwater intrusion, particularly as it will affect ground water and water supplies. There are no permanent surface streams in these islands; the ghuts (streams) are usually dry, except after heavy rainfall. Thus, the major system responses to accelerated sea level rise dealt with here will be the direct loss of coastal land, changes in the morphology of the coast, and the increased likelihood of coastal flooding (Table 4).

PHYSICAL EFFECTS

Increased shoreline erosion is likely to be one of the major effects on Antigua and Nevis. There are no long- or short-term shoreline change data for Antigua. However, a beach-monitoring program set up in Antigua in 1991 (Cambers, 1991b) should provide some data on shoreline change for the future. For this study, the figure used in Table 4 is based on qualitative personal and published observations on the Antiguan coast and long-term erosion rates for nearby islands, in particular Barbados and Montserrat. In Nevis, beach change data have been collected on a regular basis since 1988 (Cambers, 1992). Over the last four years the average erosion rate in Nevis has been very high: 2 meters per year. However, this figure includes the effect of the major hurricane *Hugo* in 1989. The erosion rate used in Table 4 has been reduced by 50 percent to 1 meter per year to give a more realistic long-term erosion rate.

The increased flooding frequency is a result of the raised water level, combined with the projected increase in the frequency and magnitude of hurricanes (Table 1).

TABLE 4. PHYSICAL EFFECTS AND NATURAL SYSTEM RESPONSES IN ANIGUA AND NEVIS

Effects and Responses	**Sea Level Rise Scenarios**					
	Base		*0.3 m*		*1.0 m*	
	Ant.	**Nev.**	**Ant.**	**Nev.**	**Ant.**	**Nev.**
Physical Effect						
Shoreline erosion (m/yr)	0.3	1.0	0.6	1.3	1.2	1.9
Flooding Frequency (1 flood in # yrs.)	1 in 5 yrs.	1 in 5 yrs.	1 in 3.5 yrs.	1 in 3.5 yrs.	1 in 2 yrs.	1 in 2 yrs.
Natural System Responses						
Production areas:						
Agriculture (km^2)	NA	0.36	NA	0.42	NA	0.62
Fishing	NE	NE	NE	NE	NE	NE
Sand mining (million cu. m.)	1.23	1.1	2.46	1.3	4.92	1.9
Urban (km^2)	0.21	0.14	0.42	0.16	0.84	0.24
Recreational beaches (km^2)	0.27	0.28	0.54	0.33	1.08	0.48
Habitats:						
Wetlands (km^2)	0.63	0.10	1.26	0.13	2.52	0.19
Beach/dunes (km^2)	1.23	1.1	2.46	1.3	4.92	1.9

NA: not applicable.
NE: not estimated.
Beach/dunes represents area of beach lost: beach length x width eroded.

NATURAL SYSTEM RESPONSES

The major natural system responses are losses of construction sand, of urban land, and of recreational beaches. There is very little coastal agriculture in Antigua, so agricultural losses were not estimated. Similarly, in Nevis, agriculture in the coastal zone is not an important activity. However, there are some coconut plantations there, so the figure in Table 4 represents the partial loss of these areas.

The major fishing industries in Antigua and Nevis are based on nearshore reef fisheries. At present, there are insufficient data on how these reefs will respond to an acceleration in sea level rise, so no attempt has been made to quantify the impact on fisheries.

Beach sand is the major source of construction sand in Antigua and Nevis, and is a major factor influencing the beach erosion there. The figures in Table 4 represent the beach length multiplied by the width of beach lost multiplied by the depth of sand that might be mined. This is potentially an overestimate, in that not all of this sand would have been mined. Nevertheless, it has been included because it provides some quantitative estimate of the different scenarios, and since sand is such an expensive commodity in the region, there is an important economic cost. (Average cost of sand in the OECS region is U.S. $20+ per cubic yard; transport is additional.)

The loss of recreational beaches shown in Table 4 represents the areas where development behind the beach makes it impossible for the beach to retreat inland and reposition itself. For instance, at Darkwood Beach on Antigua, where the road runs close to the sea, the beach would be unable to reposition itself further inland because of the existence of the major highway. It was estimated in Antigua that approximately 9 km of low-lying coastal land is heavily developed and would thus be lost as a result of accelerated sea level rise. This represents 22 percent of the total low-lying sandy beach length. On Nevis, the loss of recreational beaches would include such areas as Newcastle, parts of Mosquito Bay, and Pinneys Beach. This represents a length of 2.5 km, or 25 percent of the total low-lying coast (beach length).

Table 4 shows that a considerable area of wetlands would be lost on Antigua as a result of accelerated sea level rise. This is particularly important, because already a considerable expanse of wetlands has been lost as a result of filling in for construction activities. In contrast, on Nevis, only a small area of wetlands would be lost.

Perhaps the major loss would be the area of beach and dune land. However, in relation to the loss of recreational area, a very large percentage of these beaches (78 percent) could relocate further inland *given the present level of development*.

RESPONSE OPTIONS

The major responses as defined in the IPCC Common Methodology are: do nothing, retreat, accommodate, and protect. The Eastern Caribbean Islands are already aware of coastal zone management issues and problems, and at least some of the islands are trying to put in place effective coastal management policies, albeit with limited success. Thus, doing nothing is an unlikely response. However, it should be noted that the current level of awareness of accelerated sea level rise and its likely impacts is very low on the islands.

RETREAT

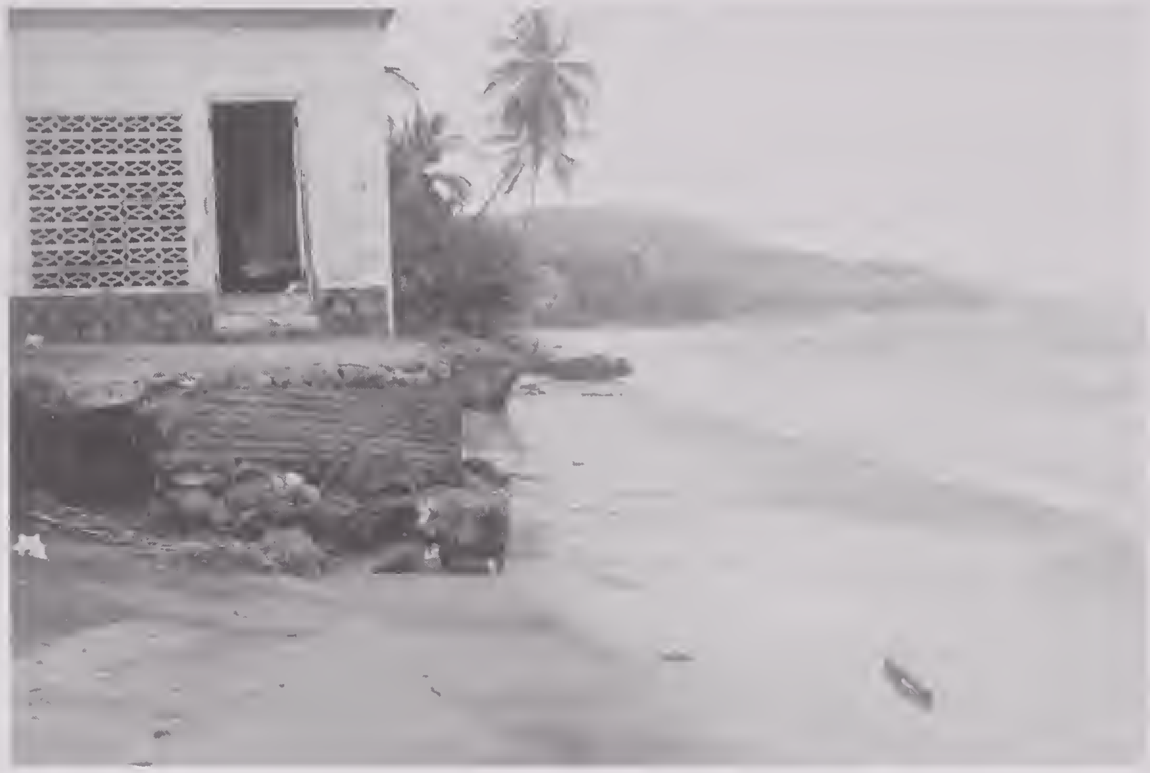
The response to retreat inland is unlikely to be favored. Often the lots are small, and there is no space for retreating inland, or else the lots are constrained by coastal highways. In addition, coastal land is so highly priced that it is necessary to use it intensively. The cost of beachfront land in the OECS islands can be as high as U.S. $20 per square foot, depending on the size of the lot.

The general perception is still that the coastline is a fixed line. Buildings damaged by storms, hurricanes, or slow erosion have often been rebuilt in exactly the same position. Only when the rebuilt structure is lost will the lot of land be abandoned or some other means of protection sought. The general perception is that the sea takes away sand and brings sand back, but that there is a "status quo" and no real long-term change. This perception is widespread and is very difficult to change, even with examples and photographs. The photographs shown in Figure 2 illustrate this point.

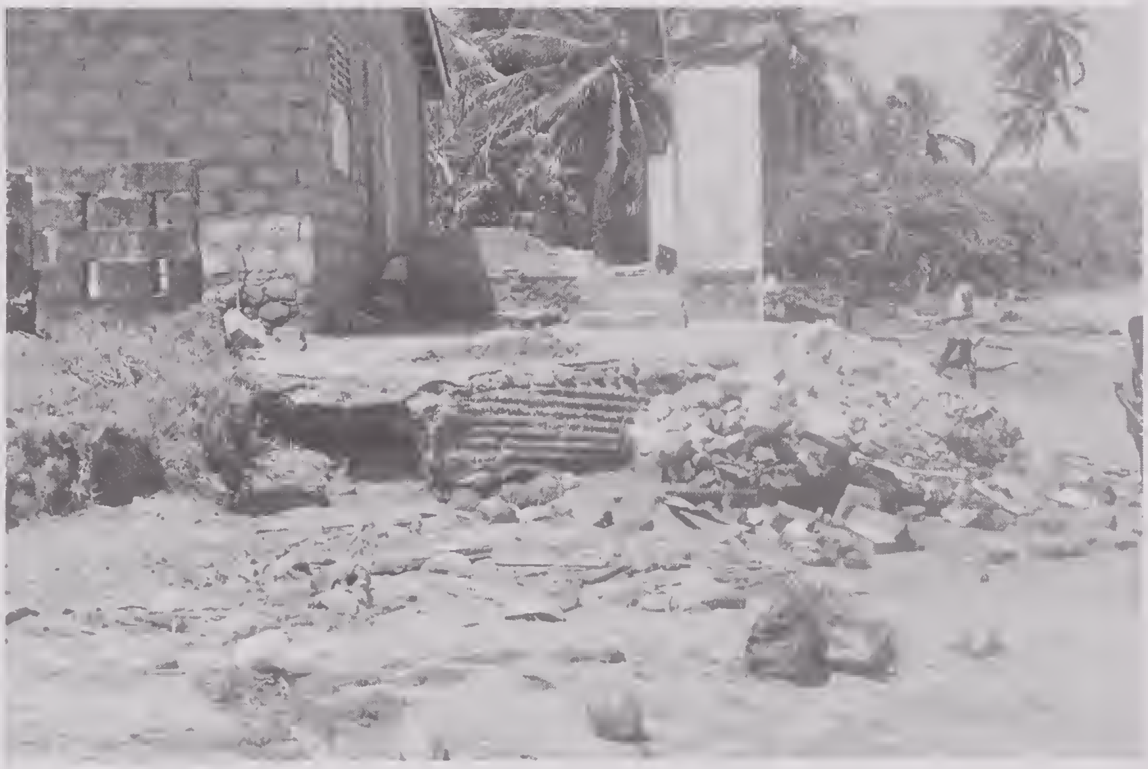
This same perception is often seen when dealing with landowners and developers and attempting to enforce coastal setbacks. Land is regarded as a permanent feature, and it is generally felt that there is a need to use all of the land intensively.

The whole idea of sea level rise as a problem is not generally recognized in the OECS. The idea of retreating and leaving land to be eroded by the sea and the idea of not being able to rebuild structures damaged in storms are not acceptable at the moment on these islands. Obviously, ideas can and will change over time, but this is the current background against which available responses must be reviewed.

FIGURE 2. LOCAL PERCEPTIONS OF COASTAL CHANGE



This house in Sauteurs, Grenada, had to be abandoned in 1984 because it was in the intertidal zone.



The abandoned house was rebuilt in 1986 on the same foundation, just 3 meters further inland and still in the intertidal zone.

ACCOMMODATE

The response to accommodate—that is, raising existing land and structures or building them on piles—may be prohibitively expensive in view of the type of development taking place on the coast at present. Much of the coastal development consists of large-scale concrete structures.

However, in relation to structures yet to be built, this response may be very useful when combined with setback policies. For example, if a coastal setback, say in Nevis, were 30 times the erosion rate, or 30 meters, but the particular lot was only 40 meters deep, the setback guideline could be relaxed, provided the structures were piled. This concept has not yet been used on the islands, but has considerable potential.

Indeed the whole concept of using coastal setbacks based on erosion rates is not used in the OECS countries, mainly because the coastal change data are not available. As mentioned earlier in this report, there are no beach change data for Antigua at present, and only four years of data for Nevis. Thus, in general the concept of coastal setbacks is poorly understood in the OECS. Guidelines are usually rigid but at the same time unenforceable—e.g., 15 meters (50 feet) from the high-water mark. The guideline is rigid in that it is a fixed distance, but difficult to enforce in that the particular high-water mark is never defined, and often what is used is the line shown on a survey plan that may be 20 years old.

PROTECT

At present, the protection option is likely to be the most favored in the OECS. The usual response following severe beach erosion is to protect the land or property with a wall or revetment or with groins. In a very few cases, breakwaters have been used, but generally their expense has proved prohibitive. The option of beach nourishment has not been extensively used in the OECS. Some attempts proved unsuccessful, particularly in St. Lucia in the early 1980's, mainly because they were not executed properly. Thus, the technique suffered some bad publicity. Another factor is that most of the volcanic islands are surrounded by a very narrow shelf (see Nevis in Table 1). Thus, the availability of sand at a suitable depth is largely unknown. In addition, the availability of suitable dredging equipment on the islands has been a constraint in the past. Against this background the likely responses are summarized in Table 5.

TABLE 5. RESPONSE OPTIONS AND PREFERENCES IN ANTIGUA AND NEVIS

Response Options	Island Preferences
Do Nothing	Most islands will attempt to implement some response strategy.
Retreat	Not a favored response because of the high value and cost of land, islands are small and land is in high demand, and other infrastructure limits this option.
Accommodate	Not a likely response for existing development, but a feasible alternative for new development.
Protect	Likely to be the most favored response. At present, solid structures are more generally accepted. Beach nourishment is rarely used.

The protection response has only been quantified for the lowland coast exclusive of wetland areas. The question of whether it is best to protect the mangrove and wetland areas with dikes or to let them accommodate by growing upwards and extending landward has not yet been resolved. So for the purposes of this first quantitative estimate, they have been left totally unprotected.

Table 6 shows the costs of protecting Antigua and Nevis. The dollar figures are based on estimates of present protection costs and, as discussed previously, the actual feasibility of beach nourishment has to be assessed and proven. However, bearing in mind the fact that the present tourism product of the OECS is largely based on the beaches, the need to protect and ensure the existence of the region's beaches is of paramount importance. As has been shown in other parts of the world, beach nourishment, possibly combined with offshore breakwaters, is a better way to conserve the beach, as compared to the land behind the beach, which can perhaps be adequately protected with a sea wall or revetment.

TABLE 6. PROTECTION COSTS FOR ANTIGUA AND NEVIS (MILLIONS OF 1992 EASTERN CARIBBEAN $)*

Protection Strategy	**Sea Level Rise Scenario**					
	Base		*0.3 m*		*1.0 m*	
	Antigua	Nevis	Antigua	Nevis	Antigua	Nevis
Sea walls/Revetments						
•Length (km)	2.5	1.5	5.5	2.5	7.5	2.5
•Cost	5.25	3.15	13.75	6.25	30.00	10.00
Breakwaters						
•Length (km)	--	--	3.0	2.0	4.5	3.0
•Cost	--	--	27.00	18.00	40.50	27.00
Beach Nourishment						
•Length of beach (km)	2.25	4.0	8.25	5.0	8.25	6.5
•Cost	11.9	21.2	87.45	53.0	131.18	103.4

* 1 U.S. dollar = 2.64 Eastern Caribbean dollars.

Assumptions:

Sea walls/Revetments

Sea wall/revetment cost for:

- Base case: EC $2,100 per meter. This would be existing sea walls that would be rebuilt and/or strengthened.
- 0.3 meter rise: EC $2,500 per meter.
- a 1.0 meter rise: EC $4,000 per meter.

The 0.3- and 1.0-meter scenarios assume that existing sea walls/revetments would be reinforced, and new ones would be built at towns on coast--e.g., Falmouth, Parham Town, airport runway.

Breakwaters

Breakwater cost EC $9,000 per meter.

For rises of 0.3 and 1.0 meters, a combined method of breakwaters and beach nourishment is envisaged.

For a 1.0-meter rise, breakwaters would be longer and perhaps higher.

On Antigua, breakwaters would be required at Dickenson Bay, Runaway Bay, Deep Bay, Lignumvitae, Darkwood, Curtain Bluff, Half Moon Bay, and Dutchman Bay.

On Nevis, breakwaters are envisaged at Pinneys Beach for the 0.3-and 1.0-meter rises.

Beach Nourishment

Base: Dickenson, Runaway and Long Bays would need one nourishment.

0.3 meters: All the bays with breakwaters and some additional ones would need renourishment twice.

1.0 meters: All the bays with breakwaters and some additional ones would need renourishment three times.

The methodology and criteria used are explained in each table. For each island it has been assumed that under the base case of no accelerated sea level rise, existing sea walls/revetments would need to be rebuilt and/or strengthened because of existing erosion that is taking place. However, no new breakwaters would be built, although limited beach nourishment would be needed to maintain severely eroding beaches, such as Dickenson Bay in Antigua and Pinneys Beach in Nevis. With a rise of 0.3 and 1.0 meters, ASLR 1 and 2 existing sea walls would have to be rebuilt, and new ones would have to be constructed to protect towns and infrastructure directly on the coast. Similarly, important tourist beaches would be protected with a combination of offshore breakwaters and beach nourishment, provided the latter alternative is feasible.

A comparison of the total cost of protection on each island is presented in Table 7. Under the base case, the estimated costs for each island are similar. This is mainly because the present beach erosion rate in Nevis is so high that it is estimated that certain measures will be needed anyway to conserve and maintain the beaches. As was discussed earlier, because coastal change data in Antigua are unknown, a lower estimate was assumed. Differences arise, however, under the 0.3- and 1.0-meter scenarios. The estimated protection cost for Antigua, with its greater length of lowland beach coast, is far higher.

TABLE 7. TOTAL PROTECTION COSTS—LOWLAND COASTS LESS WETLAND AREAS (MILLIONS OF EC $)

Country	**Costs per Scenario**		
	Base	*0.3 meters*	*1.0 meters*
Antigua	17.15	128.20	201.68
Nevis	24.35	77.25	140.40

Bearing in mind that these total figures represent only a first-order quantitative estimate, they are very high when compared with existing expenditures on coastal defenses. While exact figures are not known for each country's expenditure on sea defenses and their maintenance, annual totals are likely to be low. Often external assistance is sought for major sea defense works. The figures shown in Table 7 are likely to be 10 to 100 times the existing annual expenditure. Thus, it is unlikely that the islands will be able to meet the costs of these response mechanisms without considerable external assistance.

CURRENT STATUS OF COASTAL ZONE MANAGEMENT

Unfortunately, it is not possible at this time to follow the next step of the IPCC Common Methodology, which involves the vulnerability analysis. The information is not available at present to assess the socioeconomic values "at risk, at loss, or at change." This will require further detailed analysis of the socioeconomic factors within the coastal zone.

However, it is possible at this time to make some general statements about the choice and timing of the response strategies. Both countries described in this case study, and indeed all of the OECS, have large percentages of lowland coasts that are undeveloped. Only 22–25 percent of the lowland beaches of Antigua and Nevis is developed. This leaves 75–78 percent of the lowland beach coast yet to be developed. Thus, in one sense both Antigua and Nevis have a tremendous opportunity to accommodate future accelerated sea level rise through proper coastal management procedures. This will include such measures as coastal setbacks and adaptive building techniques, which could perhaps halve protection costs. However, the question arises as to whether either of these countries has the capability or foresight to develop such policies.

ANTIGUA

Antigua has no specific coastal management legislation. There is a Beach Control Ordinance, which effectively allows for the management of activities on beaches, such as water skiing. The Beach Protection Ordinance controls the taking of sand and gravel from the beaches. The Land Development Control Act controls all development on the coast and on the island. Under this act a 15-meter (50-foot) development setback from the high-water mark is enforced. However, in practice, many large-scale development applications are approved at a political level without recourse to the Land Development Control Authority. Several agencies are involved in coastal zone management in Antigua. These include Agriculture, Fisheries Division, Development Control Authority, Public Works, and Economic Development. However, no agency plays the lead role or coordinates the activities of others. So in effect, there is little effective or integrated coastal zone management.

ST. KITTS-NEVIS

On St. Kitts-Nevis, a National Conservation and Environment Protection Act was passed in 1987. This legislation defines the coastal zone; provides for the establishment of protected areas, beach management, and preparation of management plans and sets up a Conservation Commission. (The Act also contains provisions for the protection of plants and animals, soil and water conservation, and the preservation of antiquities and historic buildings.) The act is fairly comprehensive. However, there are some concerns. For instance, the beach is defined as extending 20 meters inland from the high-water mark and is vested in the Crown. This may yet be challenged, because it will involve the Crown taking over private land without compensation. In addition, some five years after the Act was passed, the Conservation Commission has yet to be established. Despite these reservations, the existence of the Act is a major step forward in the OECS.

St. Kitts and Nevis is one country, but each island has a separate government. In 1991, Nevis passed a Zoning Plan and Ordinance. This was a major step forward in coastal management, since it contains adequate setbacks for coastal development. No buildings will be permitted within 37 meters (120 feet) of the high-water mark, and only small, raised buildings will be permitted between 37 and 91 meters (120-300 feet) from the high-water mark. Major developments have to be located a minimum of 91 meters (300 feet) from the high-water mark. These types of setbacks, if properly implemented, could provide a model for the accommodation response to accelerated sea level rise. Obviously, since the ordinance was only passed in 1991, its effectiveness cannot be assessed for some time. Nevertheless, Nevis is certainly one of the most forward-looking of the Eastern Caribbean Islands in this respect. It remains to be seen whether the ordinance will be fully implemented.

The coastal management structure in Nevis, like Antigua, is somewhat fragmented. Several agencies are involved, including Agriculture, Physical and Economic Planning, and Public Works. A nongovernment organization, the Nevis Historical and Conservation Society, also plays a very important role as a source of technical expertise, as an environmental watchdog, and as a means to organize public support. However, there is no leading agency that fulfills the coordination role.

COMPARISON OF POLICIES

In summary, it would appear that Nevis has moved ahead in terms of mechanisms and legislation relating to coastal zone management. The framework is also in place for implementing the accommodation response to accelerated sea level rise, although it is interesting to note that this framework was designed to deal with existing beach erosion, and not future sea level rise. However, neither island has the institutional structure to carry out the goals and objectives of integrated coastal zone management.

Given the uncertainties relating to accelerated sea level rise, it is recommended that Nevis use its legislation and zoning policies to try to accommodate future rise, rather than to start implementing a protection response. Similarly, it is recommended that Antigua develop similar policies to accommodate accelerated sea level rise. In addition, tidal gauges should be established on all the islands of the OECS as a matter of priority, so that records of sea level change may be started.

ASSESSMENT OF NATIONAL CAPABILITY

Table 8 provides an overview of the islands' capabilities to implement the response options. The table follows the general format suggested in the IPCC Common Methodology.

The legislative, institutional, and organizational capabilities all present problems in Antigua. The only exception is staff motivation, which is fairly high. People, especially within the government, are keen and interested. The situation is slightly better in Nevis, particularly with regard to legislation and regulations. Staff motivation is similar to that in Antigua: people are interested and wish to know more.

Both islands are similar regarding their economic and financial capabilities. All of these aspects are a problem. Certainly, the islands themselves cannot support the response options, and regional funding agencies have not yet been identified. Financial capabilities and arrangements may also be a problem.

The table does not include technical institutions. No specific institutions are located in Antigua or Nevis. However, three major organizations with some skills in sea level rise that cover the OECS are:

1. OECS Natural Resources Management Unit—A technical coordinating agency set up in 1986 and mainly funded by Germany. It coordinates projects and hires consultants.

2. UNESCO COMAR (Coastal & Marine Research & Training) COSALC I Project—Beach and Coastal Stability in the Lesser Antilles. This regional program aims to strengthen local capabilities to manage and monitor beaches and coasts and has been ongoing since 1985.

3. University of the West Indies—This University has campuses in Barbados, Trinidad, and Jamaica and has some expertise in the field of sea level rise.

As was explained earlier, there are several cultural and social constraints restricting the options. Thus, in Antigua, this is seen as a problem at all levels. In Nevis, there has been some success with awareness and public education programs, largely due to the efforts of the Nevis Historical and Conservation Society.

TABLE 8. CONSTRAINTS RELATED TO IMPLEMENTATION FEASIBILITY IN ANTIGUA AND NEVIS

Constraints	Problem		Partial Problem		No Problem	
	Antigua	*Nevis*	*Antigua*	*Nevis*	*Antigua*	*Nevis*
Legislative/Institutional/ Organizational						
Level A						
Existing legislation	X					X
Existing inst./org.	X	X				
Executive powers	X	X				
Level B						
Special tasks/responses	X	X				
Communications structure	X	X				
Staffing/facilities	X	X				
Existing CZMP plan, etc.	X			X		
Level C						
Staff education level	X	X				
Knowledge man/capability	X	X				
Staff motivation			X	X		
Economic/Financial						
Level A						
National economic bearing capability	X	X				
Level B						
National/regional funding possibilities	X	X				
International funding possibilities	X	X				
Level C						
Financial management capability	X	X				
Cultural/Social						
Level A						
Cultural	X	X				
Socioeconomic	X	X				
Level B						
Cultural programs	X			X		
Socioeconomic programs	X	X				
Level C						
Recent cultural achievements	X			X		
Recent socioeconomic achievements	X	X				

IDENTIFICATION OF NEEDS

In 1991, the British Overseas Development Administration commissioned a study on the likely impacts of sea level rise, climate change, and ozone depletion for the OECS region. Phase 1 of the study (Bass and Cambers, 1991) described in a qualitative manner the likely impacts and assessed the region's resources and capabilities to deal with those impacts and to develop the necessary responses. Terms of reference were developed for a more substantive Phase 2 of the project. This would include:

- Quantitatively assessing the implications of sea level rise and the formulation of response options using a detailed case study approach.
- Setting up tidal gauges to monitor sea level rise on each island.
- Preparing a regional climate prediction and climate scenarios.

An awareness and education component was built into all three sections. It was proposed that a later Phase 3 would determine the impacts of climate change on agriculture, forestry, nature conservation, water, fisheries, and land use. The detailed climate prediction was a necessary input for Phase 3. It was estimated that Phase 2 would cost U.S. $500,000.

The project proposal for Phase 2 was approved by the OECS Heads of Government at the Twentieth Meeting in January 1992. The funding for the project is currently being sought.

This study should provide a detailed quantitative assessment of impacts and responses for the eight countries of the OECS. However, assistance is needed in other areas, as can be seen from Table 8. In particular, assistance is required in preparing coastal zone legislation: St. Kitts-Nevis is the only country in the OECS that has comprehensive coastal zone legislation. Assistance is also required with institutional strengthening and training, such that effective integrated coastal zone management can be achieved. There is also a need for coastal zone management plans; as yet no country within the OECS has started preparing such plans.

Finally, there is a low level of perception and understanding of sea level rise issues in the OECS (Bass and Cambers, 1991). Thus, additional assistance is required to raise the level of awareness. However, such issues as climate change and sea level rise are often viewed as too large and too remote by these small island states. So there is a real need to combine projects dealing with sea level rise with ongoing projects, such as programs for coastal zone management, disaster preparedness, and beach monitoring.

CONCLUSION

The use of the IPCC Common Methodology to assess the vulnerability of the coastal areas of Antigua and Nevis to sea level rise has proved useful, even though the full analysis could not be completed in this paper. It has shown quite clearly the strengths and weaknesses of these two countries with regard to their capabilities to respond to and implement the various response options.

The islands of the OECS, while being at the forefront in experiencing the impacts of sea level rise, have relatively long lengths of undeveloped coastlines. Thus, they possess the ability, at least in part, to accommodate accelerated sea level rise. However, considerable external assistance is required to enable these small island states to optimize this advantage.

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PRELIMINARY ASSESSMENT OF THE VULNERABILITY OF KIRIBATI TO ACCELERATED SEA LEVEL RISE

Colin D. Woodroffe
University of Wollongong
Wollongong, Australia

INTRODUCTION

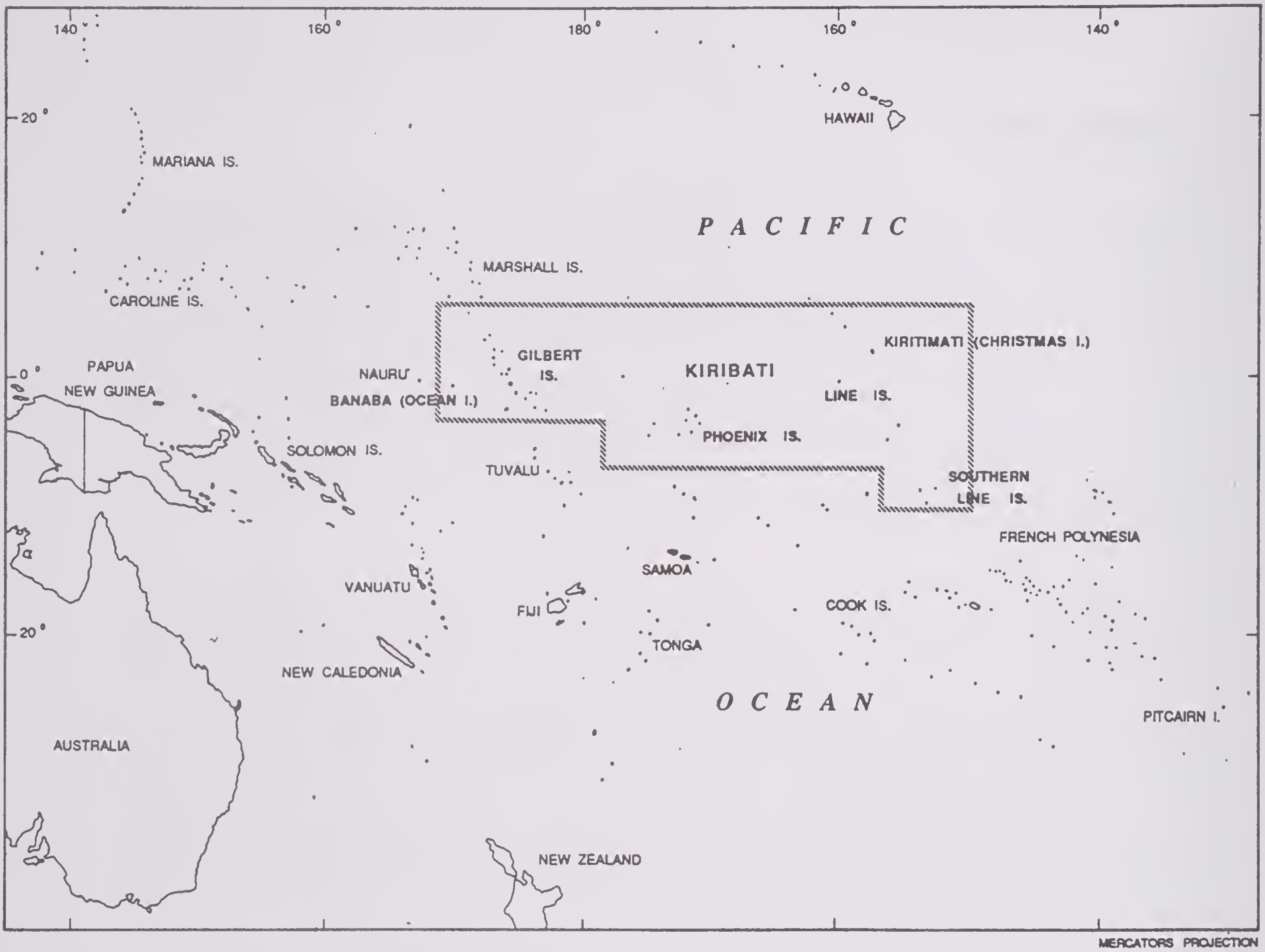
The Republic of Kiribati, in the Central Pacific, comprises 33 small islands, almost all of which are atolls, straddling the equator and the International Date Line (Figure 1). Kiribati has three distinct archipelagoes: the western Gilbert Islands chain, which comprises 17 islands stretching from 2.5° north to 1.6° south of the equator; the Phoenix Islands group, comprising 8 islands, all in the Southern Hemisphere; and the Line Islands group, comprising 8 islands, spread over more than 2,000 km of sea (Figure 2). Flint and Caroline islands, in the southern Line Islands, are more than 4,000 km from the capital of Kiribati, Tarawa, in the Gilbert Islands. These islands account for a total land area of around 820 km^2, of which the island of Kiritimati (Christmas) in the Line Islands comprises more than half, and a sea area of 3.55 million km^2. The islands are generally low-lying and composed of poorly consolidated sands. The one exception is the island of Banaba, which is a limestone island that rises to 78 meters; this island has been extensively mined for phosphate.

The islands of the Republic of Kiribati are all small and low, and thus appear especially susceptible to anticipated sea level rise. Coral atolls are ring-shaped reefs in the middle of the ocean, with a discontinuous fringe of sandy reef islands around their central lagoon. On smaller reef platforms there may be no central lagoon, but only one island in the center; these are termed reef-top islands, or table reefs. Figure 3 shows the outlines of the coral atolls and the reef-top islands (i.e., Tamana, Arorae, Nikunau, Beru, Makin, and Kuria) of the Gilbert Islands. It can be seen that many of the atolls consist of land only along their eastern margin, and that often consists of a chain of small islands. All are small in surface area, but where there are a large number of individual islands, they have a large perimeter. Thus, the reef-top island Nikunau consists of one island on its reef platform with a surface area of 19.9 km^2 and a perimeter of 31 km, but the neighboring atoll of Nonouti has more than 18 individual islands with a similar total land area of 19.8 km^2, but a total perimeter of over 155 km!

The concern of the people of Kiribati (I-Kiribati) about the vulnerability of their country to sea level rise has been expressed by the former president of Kiribati, the Honorable Ieremia Tabai, who has said: "If the greenhouse effect raises sea levels by one meter it will virtually do away with Kiribati.... In 50 or 60 years, my country will not be here." Broad assessments of the vulnerability of nations to sea level rise have suggested that Kiribati is one of the most vulnerable of all nations (Tsyban et al., 1990). Thus, in assessing South Pacific nations, Pernetta (1988) placed Kiribati in the most vulnerable category, along with Tokelau, Marshall Islands, Tuvalu, and the U.S. Line Islands. Articles in the popular press, including the *Pacific Islands Monthly*, have speculated that the islands of Kiribati "may disappear forever" (Roy and Connell, 1989).

A rapid preliminary assessment of the vulnerability of the Kiribati nation to accelerated sea level rise was undertaken in February 1992, using the Common Methodology compiled by the Intergovernmental Panel on Climate Change (IPCC). The study (Woodroffe and McLean, 1992) was based upon existing knowledge and available data, and the authors' previous research experience in Kiribati, and included limited fieldwork in Tarawa, Maiana, and Onotoa.

FIGURE 1. LOCATION OF KIRIBATI IN THE CENTRAL PACIFIC



CHARACTERISTICS OF THE STUDY AREA

SOCIOECONOMIC CHARACTERISTICS

The gross domestic product of Kiribati was $40.7 million (Aus.) in 1991. The country has an extremely narrow economic base, dependent on copra production and fish exports (both took a

FIGURE 2. ISLANDS AND ISLAND GROUPS IN KIRIBATI

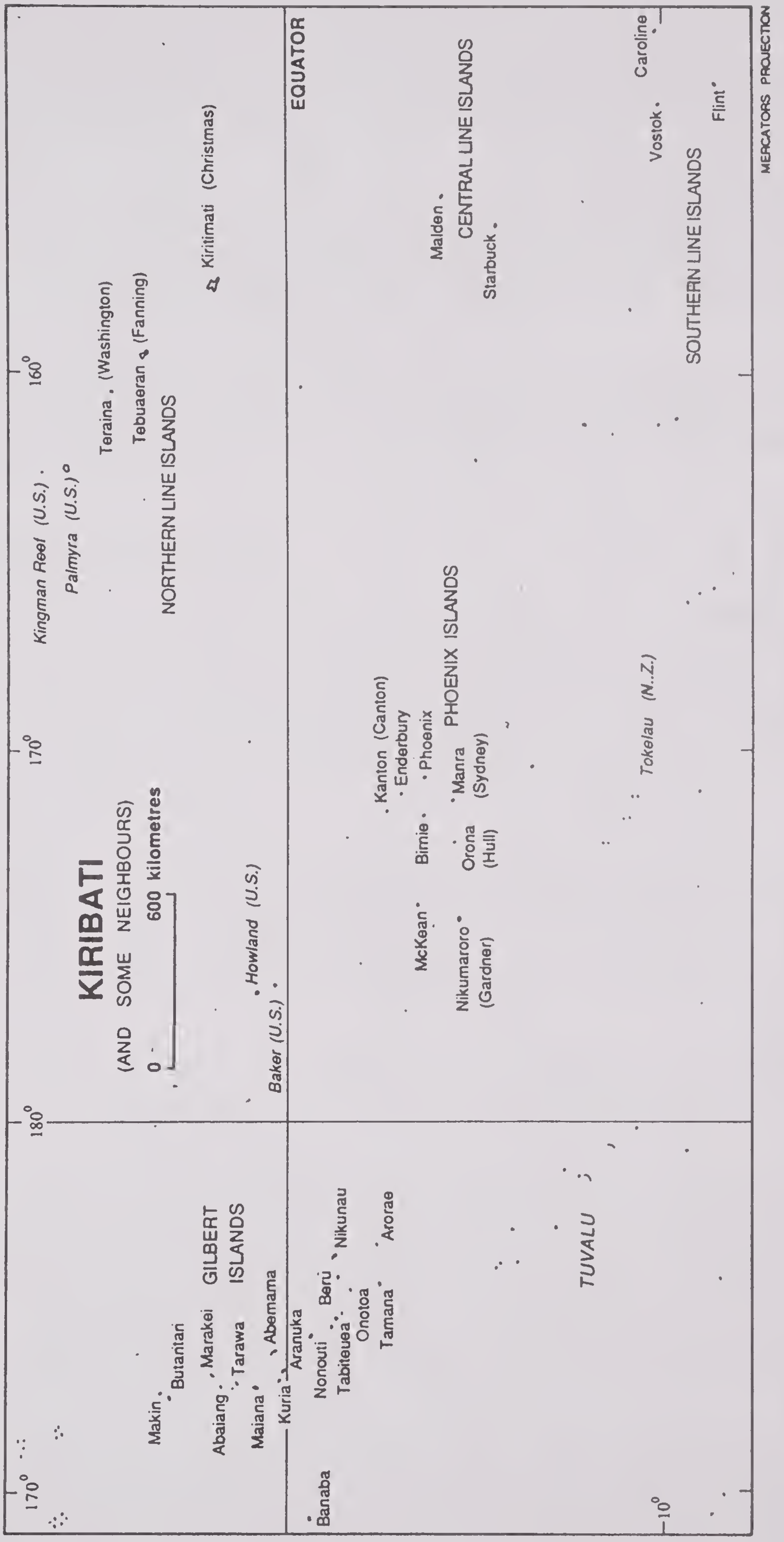
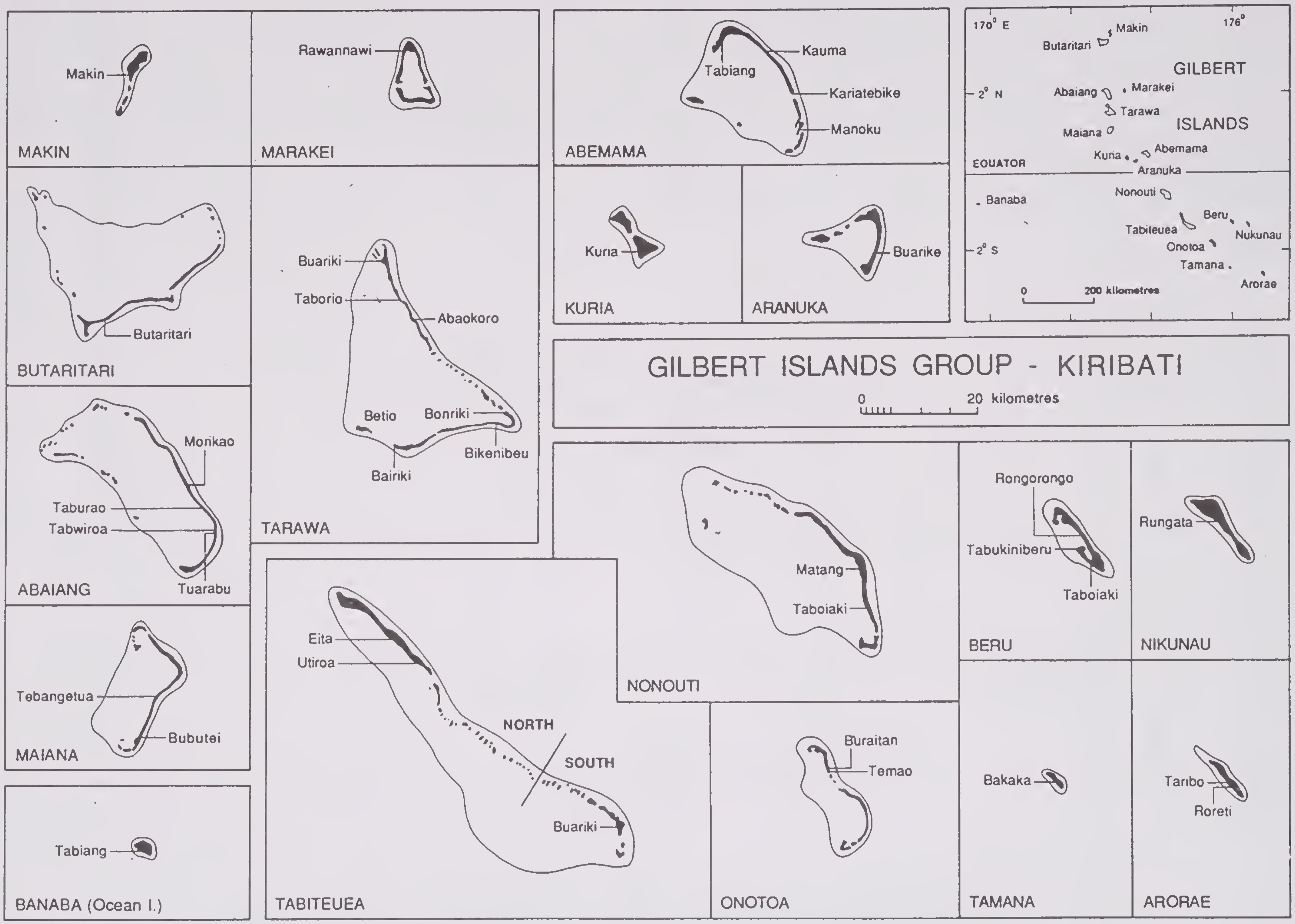


FIGURE 3. REEF AND ISLAND OUTLINES, GILBERT ISLANDS



downturn in 1990), and substantial foreign budgetary assistance. The Kiribati economy combines a rather limited cash economy with a traditional subsistence economy. These are inextricably interlocked and cannot be effectively compared using the benefit/cost procedures advocated in the IPCC Common Methodology. In Kiribati as a whole, less than 20 percent of the population is engaged in the cash sector; on South Tarawa, the figure is around 35 percent; and on the outer islands, it is generally less than 10 percent.

The population of Kiribati was 72,298 at the 1990 census, and has been increasing at 2.2 percent per year. There has been rapid urban growth on South Tarawa, combined with migration from the outer islands, with increasing, unacceptable levels of overcrowding on two of the smaller islands, Betio and Bairiki. This population pressure is already perceived as a major environmental problem on Tarawa (National Task Force, 1992).

At present the country's major developments relate to improving infrastructure, particularly through the construction of causeways. For such infrastructural projects, as for the construction of any "protective works" that might be needed in the face of accelerated sea level rise, Kiribati is dependent upon international aid.

PHYSICAL CHARACTERISTICS

A typical transect of a reef island in Kiribati is that of Bikenibeu, Tarawa, shown in Figure 4. The island is saucer-shaped, with the center lying below the level of most high tides, but protected by a ridge on the ocean and lagoon shorelines. The location of the shore is partly determined by the outcrops of coral conglomerate, which also decrease the vulnerability of this part of the island, compared to those parts not underlain by such rock. Tidal range in Kiribati is about 2 meters, and the reef flat is exposed at low tide, indicating the general lack of "freeboard" on both the ocean and lagoon shores.

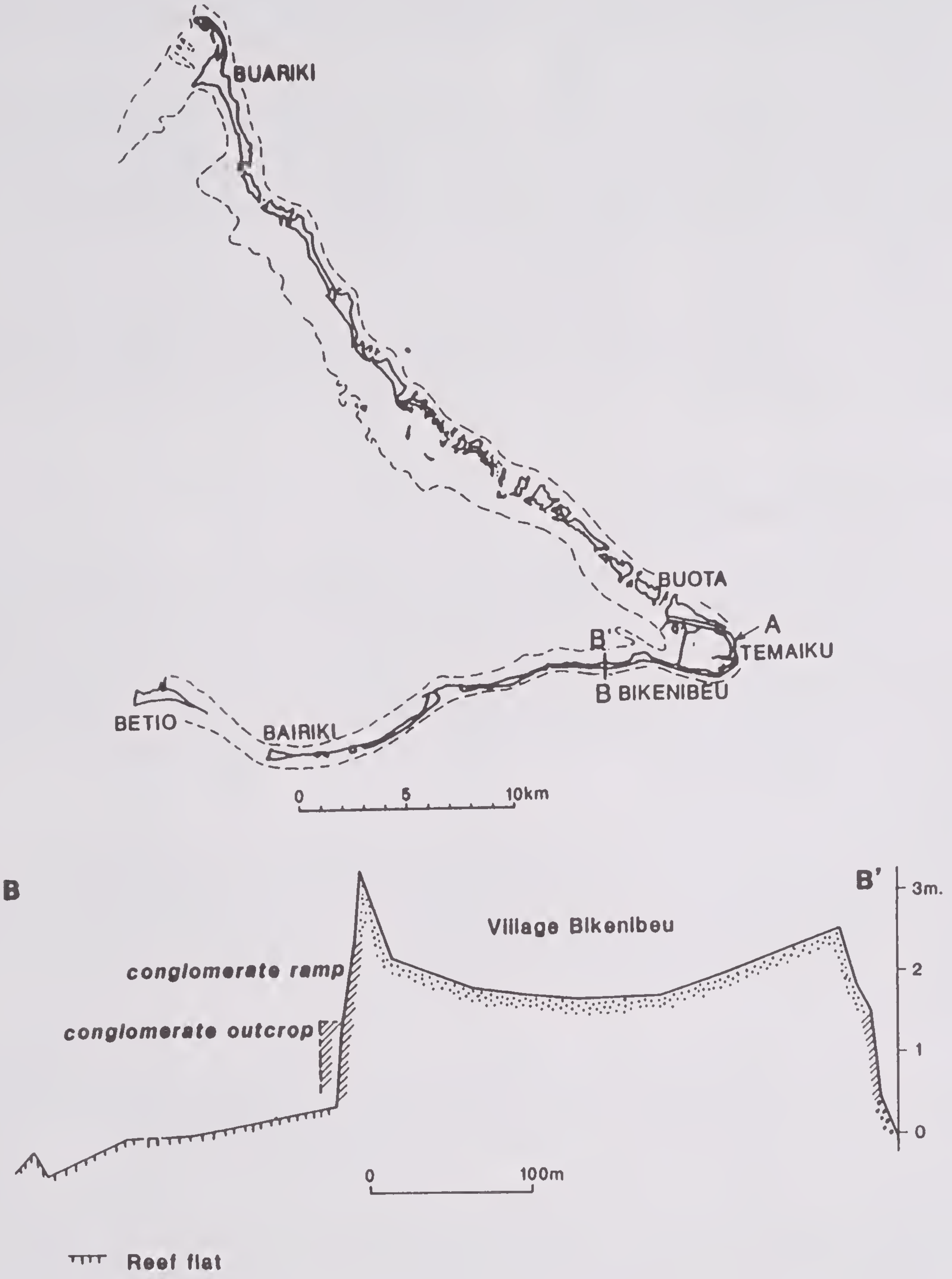
All of the islands of Kiribati are low-lying, generally nowhere reaching more than 3 to 4 meters above mean sea level. It is, therefore, important that all areas of Kiribati be incorporated into a full vulnerability profile of the nation because the *entire country* is vulnerable to the impacts of sea level rise (the freshwater table oscillates with the tides throughout each of the islands). Only a couple of case studies will be examined in this report, and even for these, much of the data are incomplete.

The best available topographic information for most of the islands in Kiribati are the topographic maps and the several sequences of vertical aerial photographs. The latter, in particular, represent an important and underexploited environmental data base.

The reef islands of Kiribati are geologically very young, and their development has been associated with fluctuations of sea level in the past (Schofield, 1977). Most of the islands appear to have developed in the last 3,000 to 4,000 years when the sea was at a level around 1 meter above present (McLean, 1989). Since that time, the sea level has fallen to its present level. The sediments of the islands are entirely calcareous, formed from the skeletal remains of organisms, such as corals, coralline algae, foraminifera, and mollusks, and are continuing to be produced on the reefs and in the lagoons. This is one important respect in which these reef islands differ from beaches in a noncarbonate setting.

Although all of the islands of Kiribati are formed on coral reefs, there are a range of coastal types, representing various grain sizes and stages of lithification. (There are two important coastal rock types, conglomerate and beach rock, which serve to protect the shoreline against erosion where they occur). Each of these coastal types exhibits a different degree of vulnerability

FIGURE 4. TARAWA, SHOWING LOCATION OF ISLANDS AND A TRANSECT ACROSS BIKENIBEU



both to present erosional and accretional forces, and to accelerated sea level rise. Coastal vegetation communities, particularly mangroves, also protect the coast, and decrease shoreline erodibility. There is, therefore, a need to develop a coastal zone mapping methodology for Kiribati (and other coral atoll nations) that will discriminate vulnerability to coastal hazards in more detail than those coastal types outlined in the Common Methodology. An example of the sort of mapping proposed is given in this paper in the case study of the island of Buota.

The shorelines of reef islands in Kiribati are naturally dynamic. Sediment is continuing to be produced, beaches both accrete and erode, and there are seasonal and year-to-year shifts in the patterns of sediment movement. There are some data on the dynamics of Kiribati reef islands, but these come principally from monitoring the effects of the Betio-Bairiki causeway. Thus, it is difficult to distinguish between natural changes and those that might result from the causeway itself. Nevertheless, each of the geologists who have examined the issues related to the impact of causeways has stressed the natural dynamics of the shore (i.e., Howorth, 1983; Howorth and Radke, 1991; Gillie, 1991).

Many of the beaches in Kiribati show signs of recent erosion. Erosion, however, may be short-lived in some cases, or severe in others. By and large, in South Tarawa and on Abaiang, the oceanward beaches appear to be accretionary, still growing from the accumulation of reef flat sediments, while lagoon shorelines are considerably more dynamic in terms of erosion and accretion cycles (Harper, 1989). Seasonal reversals of sediment movement, or reversal of general trends, such as the return of sediment back along lagoon shorelines under westerly winds, play important roles in sediment redistribution (Byrne, 1991). These movements are natural and are important, as they are the way the beach adjusts to fluctuating processes. Sea walls and other engineering structures interrupt these movements, which in turn can have detrimental effects on the downdrift shoreline.

It is also important to stress the great variability of conditions at present in Kiribati, both geographically, and from year to year. There are large fluctuations in rainfall related to El Niño, which serve to put large stresses on the economy of several islands in drought years. There are also large fluctuations in sea level from year to year, also related to El Niño. The low sea level rise scenario of 0.3 meters/year represents a total rise by the year 2100 that is less than the range within which the monthly mean sea level presently fluctuates.

IMPACTS OF SEA LEVEL RISE

In view of these uncertainties, there can be no consensus as to what effect sea level rise will have on the reef islands. At least three different types of impact have been forecast: erosion of sediment from the shore, redistribution of sediment on the shore, or accretion of new sediment onto the shore. Each of these potential responses has been suggested as the most likely by different scientists.

Erosion of the shoreline is predicted by the Bruun rule (Bruun, 1988), which is often used by engineers in noncarbonate settings as an indication of how the shore will respond to a rise in water level. When the response of shorelines to past sea level rise is examined from the geological record, the Bruun rule does not seem so appropriate, as it appears that the shoreline (and the sediment contained within the coastal compartment) has moved landward with sea level rise, preserving an equilibrium profile (Thom and Roy, 1988). On the other hand, a higher sea level will lead to deeper water across the reef flats in front of the islands, which will permit greater growth and carbonate production by corals, foraminifera, and other organisms on those reef flats (though this will in turn depend upon the health of the reef), and thus an increase in sediment production. Several reef scientists believe that sea level rise will lead to increased sediment buildup on reef islands at least in the short term (Hopley and Kinsey, 1988). The effect of accelerated sea level rise on ground water resources remains uncertain, but is largely dependent upon the response of the islands themselves.

SPECIFICATION OF SEA LEVEL RISE SCENARIOS

The majority of the islands of Kiribati are probably subsiding at an imperceptibly slow rate (<0.2 mm/year), based upon geological interpretation of the stratigraphy of the island of Tarawa (Marshall and Jacobson, 1985). The IPCC "Business-as-Usual" high and low scenarios were adopted as accelerated sea level rise scenarios for this study (0.3- and 100-meter rises, respectively, by 2100; Warrick and Oerlemans, 1990; see Table 1).

Despite the scenarios used for this study, preliminary analysis of sea level trends reconstructed from tidal gauges in the Pacific indicates that, at present, they do not show as rapid a rise as elsewhere in the world (Gornitz and Lebedeff, 1987; Gornitz, 1990; Wyrtki, 1990). The four tidal gauges located in Kiribati, although only having reliable records for about 15 years, exhibit substantial short-term fluctuations, but do not show a significant rising trend (McLean, 1989). Similarly, large intertidal corals from Kiribati, termed "microatolls," indicate recent fluctuations in water level, but do not indicate an unambiguous trend of rising sea level (Woodroffe and McLean, 1990). On the other hand, Kiribati experiences pronounced seasonal and interannual variations in water level, related to El Niño, with mean sea level fluctuating by up to 40 cm from year to year. Indeed, in late 1982 the monthly mean sea level was up to 28 cm above the long-term mean, and thus close to the long-term mean that would be expected at around 2100 under the IPCC low scenario. Of course, when the long-term mean reaches this level, these fluctuations will still be superimposed upon it.

TABLE 1. BOUNDARY CONDITIONS RELATED TO ACCELERATED SEA LEVEL RISE

Boundary conditions **Accelerated sea level rise**	**ASLR1**	**ASLR2**
sea level increase by 2100	300 mm	1000 mm
average rate of change 1990-2030	3.3 mm/yr	5.8 mm/yr
average rate of change 2030-2070	3.3 mm/yr	10.5 mm/yr
average rate of change 2070-2100	3.5 mm/yr	13.0 mm/yr
maximum rate of change	3.5 mm/yr	15.0 mm/yr
estimated rate of subsidence	0.1-0.2 mm/yr	0.1-0.2 mm/yr
relative sea level increase by 2100	290 mm	990 mm
subsidence-corrected maximum rate of change	3.3 mm/yr	14.8 mm/yr

IDENTIFICATION AND SPECIFICATION OF RESPONSE STRATEGIES

The people of Kiribati do not have an option to retreat from accelerated sea level rise. All of the islands of the nation are vulnerable to some extent, and there is nowhere to which they could retreat. There are at least two islands, Banaba and Kiritimati, that would not be severely affected by either the low (ASLR1) or the high (ASLR2) scenarios (Table 1). The effects on the other islands remain uncertain. Relocation of the population to Banaba is not feasible because it has been mined for phosphate and has not been rehabilitated. Kiritimati, on the other hand, is one of the driest atolls in the world, with an average annual rainfall of 882 mm. It contains extensive saline pools in its interior, has limited potable water, and coconut production or other agricultural potential is low (Jenkin and Foale, 1968).

One further retreat option is the total emigration of the population from what is now Kiribati. This has been suggested as the long-term solution by some researchers who take the view that the islands will erode catastrophically if the sea rises at the more rapid of the rates predicted (Connell and Roy, 1989). There seems to be no basis upon which to expect catastrophic erosion in the next 30 years, the time scale to be examined as a part of the Common Methodology. Therefore, the emigration response remains an option, but it is not considered further in this study.

The full protection option was considered, as suggested in the Common Methodology, but it is clearly impossible to protect the entire nation, as it has an enormous perimeter, despite its small surface area. It is difficult to express this in terms of value of land protected versus costs of protection in the case of Kiribati. This is because land values are not market-driven in the way that they might be in other economies. The traditional pattern of land tenure is still practiced widely. The government purchased land in the Line and Phoenix islands in recent years at a rate of around Aus. $2,500/ha ($1,000/acre), and this is the figure that is still used as "land value" on most of the outer islands. Recent purchases of land on South Tarawa have been at around Aus. $10,000/ha. The cost of building sea walls is generally around $200 to $250/linear meter, though it should be added that many people have built walls protecting their own property against erosion, using "family labor" and local materials at an unknown, but lesser cost.

None of these costings, however, takes into account the quite considerable maintenance costs of any coastal protection, the escalating environmental costs of collecting constructional slabs or fill from reef flat or lagoon, or the consequences of altered patterns of sediment movement, erosion, and accretion. (Note that mining the reef flat in front of islands is likely to lead to greater wave energy reaching the shore, and probably enhanced shoreline erosion.) In any case, the Kiribati economy is unable at present to meet the costs of infrastructural developments, such as causeway construction, and would be dependent upon aid to pay for such large-scale coastal protection. This is demonstrated in more detail in the case study of Betio in this paper.

Measures that accommodate sea level rise seem the most appropriate, perhaps involving various planning strategies, as well as some infill or reclamation of selected islands, at least until an acceleration of sea level rise can be demonstrated relative to Kiribati, and the initial consequences for the dynamics of reef islands cab be monitored. There will need to be more work done to examine in detail the accommodation options.

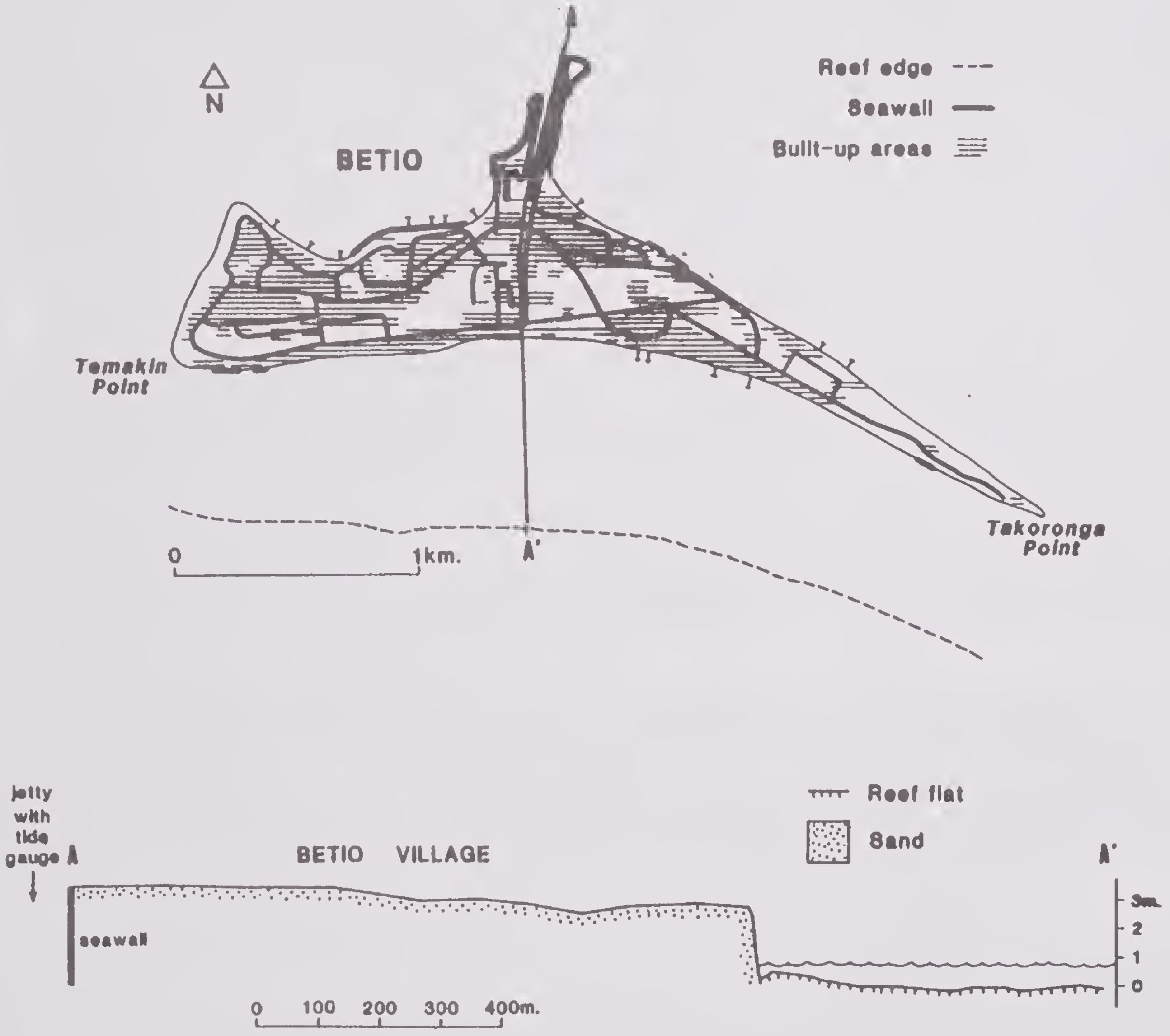
CASE STUDY 1: BETIO

The island of Betio is the westernmost island of South Tarawa and has the highest population density. There were 9,226 people on Betio in the 1990 census, which reported a population density of 5,525 persons/km^2 and a population growth rate of 2.55 percent, similar to the national average. The island can be regarded as one impact zone for the purposes of this example, although the vulnerability of the coast around the island varies substantially, as the island has various natural coastal types, including conglomerate and beach rock that afford it some protection. Of the total perimeter of 8.1 km, 2.6 km are already protected by sea walls of some type. The reef flat and lagoon surface around Betio have been extensively modified, mined, and reworked, leaving little natural habitat to be preserved. Coastal vegetation is still an important element of the natural protection of the shorelines.

There are good maps and survey data for the island, but a more detailed ground survey will be necessary to relate all survey data to tidal water levels. However, there is little data on wave patterns and wave run-up, so that tidal levels may not give a true indication of areas subject to wave incursion. Figure 5 shows a profile across the reef flat and island. It demonstrates the flat nature of the island's topography, and its closeness to present high-water mark.

Land values probably reach their highest in Kiribati on Betio (Aus. $10,500/ha), although as indicated above, it remains difficult to put true values on the land. The island contains abundant coconut palms that contribute to the life of a large proportion of the population, and the combination of cash and subsistence economy renders extension of the IPCC Common Methodology to full vulnerability analysis inappropriate.

FIGURE 5. BETIO, TARAWA: AN URBANIZED, HIGHLY POPULATED ISLAND



On Betio there exists the best set of data on physical changes for any of the islands of Kiribati. Coastal profiles have been surveyed and monitored (as often as twice a year) for over 10 years, largely to assess the impact of the causeway. Both erosion and accretion are recorded around Betio over that period, with erosion of up to 15 meters and accretion of up to 8 meters being recorded over one 18-month period (Howorth, 1983). The complexity of shoreline changes experienced at present, while possibly partly a function of the causeway and human modification of the reef flat and lagoonal environment, indicates the difficulty in predicting shoreline response to fluctuating mean sea levels, and it would be premature to speculate on the amount of erosion or accretion that would be expected under accelerated sea level rise.

The island of Betio represents the most urbanized and least natural of any of the islands of Kiribati. It already has one of the highest ratios of sea wall to nonprotected coastline. It would appear particularly vulnerable to accelerated sea level rise, and indeed much of the island would be flooded by regular high tides under ASLR2. Further protection is likely to be required. Using the costs for sea wall construction described above, it can be estimated that protecting the 5.5 km necessary for full protection under ASLR1 at $250/meter would represent a capital cost of $1,375,000. Protecting against ASLR2, though the costs are more speculative (let us say $500/meter), would appear to cost $4,050,000 for the entire island. Using the quoted land values, and assuming an erosion rate of 5 meters a year (which is probably excessive; it has been emphasized above that accretion and not erosion may be one of the more immediate responses to sea level rise), the capital loss would be around $28,875/year. There is also a considerable, but unmeasurable, subsistence loss.

The Kiribati economy is unable to meet the capital cost for an infrastructural project such as protection of this order would represent, and has sought aid from a friendly donor country to meet such infrastructural needs in the past. The tidal and the coastal survey data exist for Betio for a far more detailed appraisal of past and current erosional trends and their relationship to water level changes. Such an appraisal should be the next stage in the vulnerability assessment of Betio.

CASE STUDY 2: BUOTA

Buota, at the eastern end of the South Tarawa road, is a small and relatively undeveloped island that is undergoing rapid urbanization. This is reflected in the very high rate of population increase (12.5 percent). Even the 1990 figure of 591 people, however, is almost certainly an underestimate, as there is a high incidence of squatters settling on land that they do not own in this part of Tarawa. The squatter problem only serves to compound the rational economic approach advocated in the IPCC Common Methodology.

The island, of area 0.88 km^2, was mapped in considerable detail during field work for this project, in order to attempt to develop a vulnerability index that could be used more extensively in Kiribati. Figure 6 shows a typical topographic transect across the island, surveyed in order to examine how much of the island lies above the present high-water mark. The island reaches an elevation of more than 3.5 meters above the reef flat, and the highest point is on the oceanside beach crest. The extreme high-water mark is close to the ridge crest, and complete overwash looks imminent. Nevertheless, the island does not appear to have been inundated, even during those periods when the mean sea level has been uncharacteristically elevated.

Figure 7 maps coastal types for Buota, extending the range of categories from those advocated in the Common Methodology, in order to show features that provide natural protection for the shoreline. Outcrops of coral boulder conglomerate (formed as a probable reef

FIGURE 6. TOPOGRAPHICAL TRANSECT OF BUOTA, TARAWA

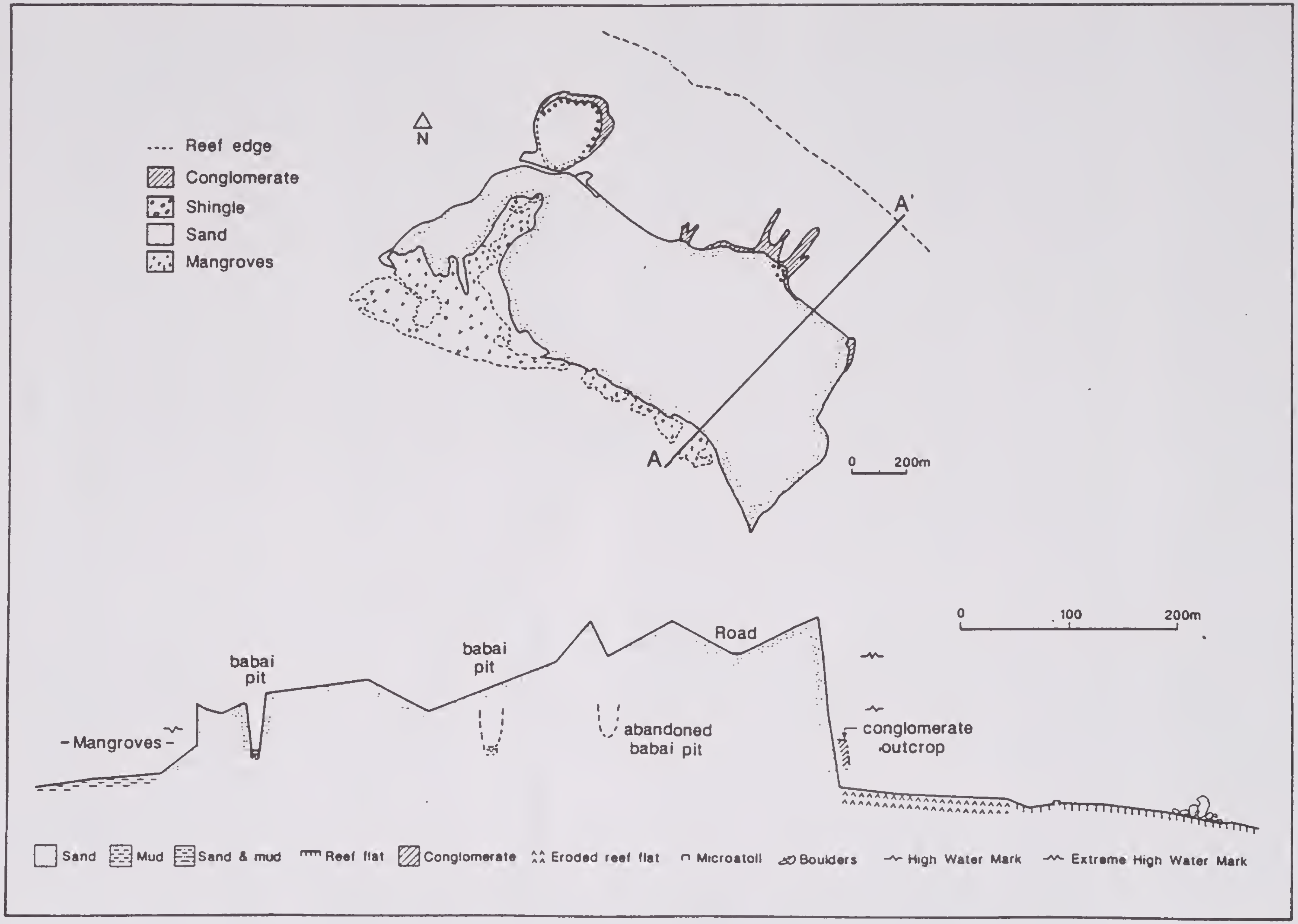
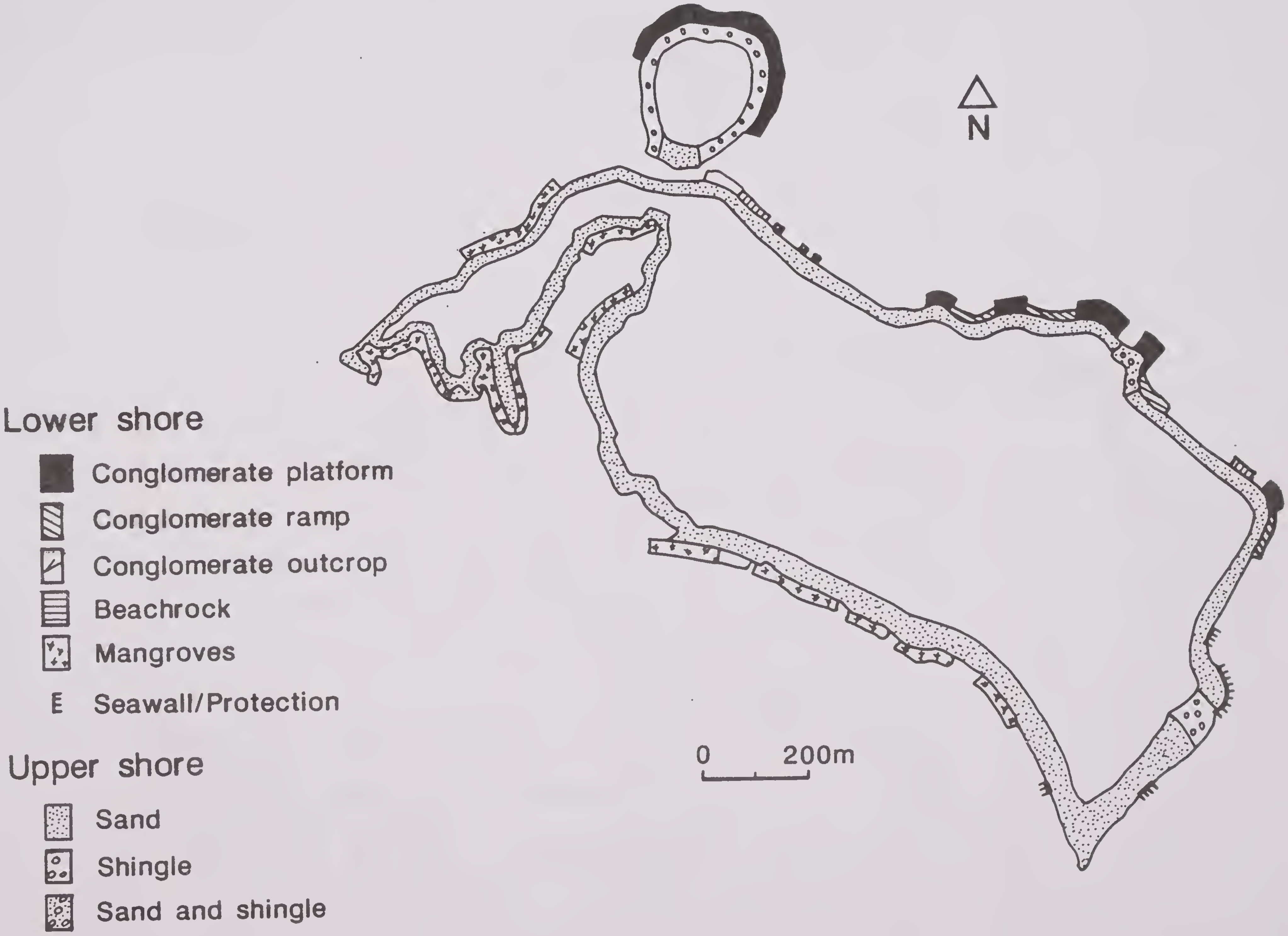


FIGURE 7. COASTAL TYPES OF BUOTA



flat deposit around 3,000 to 4,000 years ago when the sea was higher than present) protect the oceanside beaches, and sometimes other parts of the island, too). On Buota, conglomerate occurs as broad platforms stretching toward the reef crest across the reef flat, and as conglomerate ramps, steep, scoured rocky beachfronts that reflect past erosion of the platform. There are also outcrops of beach rock (a cemented beach sand). In terms of the efficiency with which these rocky outcrops prevent erosion of islands behind them, platforms exceed ramps, which in turn exceed beach rock outcrops. The small island of Naninimai, north of Buota, formed on an extensive conglomerate platform, is composed of shingle ridge and appears to still be accreting.

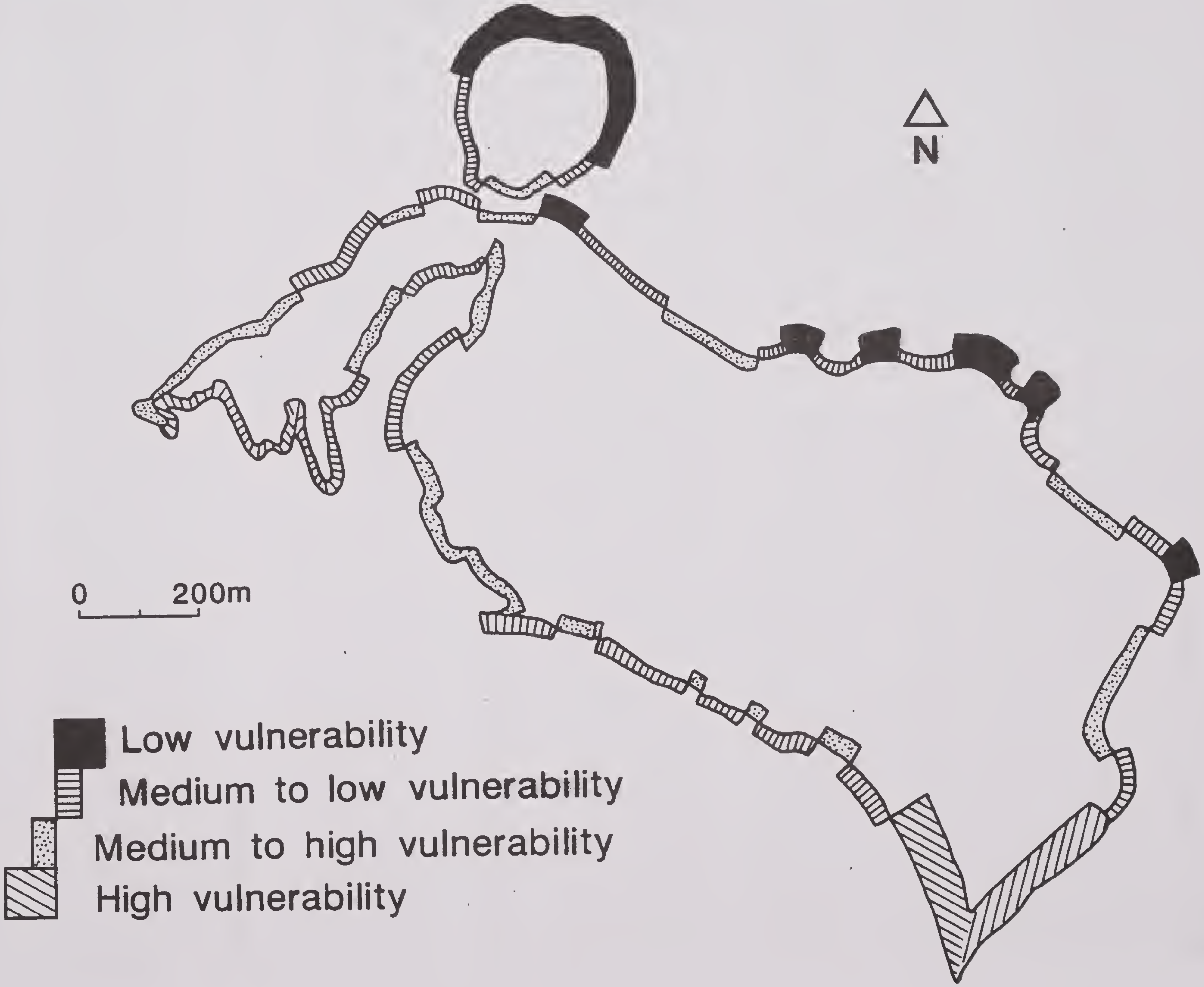
On the lagoon shore, mangroves prevent waves generated by the westerly winds from scouring the lagoon beach. Hence, they are important shoreline stabilizers, and promote sedimentation in their own right.

Figure 7 represents an attempt to develop a coastal zone mapping procedure based on these coastal types. The procedure could be used to generate an index of vulnerability (Figure 8) and will enable detailed tables of natural system data, as required by the Common Methodology (Table 2). This index represents a measure of the stability of the coast, assessed on a rapid survey, and can thus be used as a hazard index, not only to plan for changes associated with accelerated sea level rise, but also for more immediate coastal zone planning and management. In addition to field work, the preliminary mapping was based upon a comparison of aerial photographs of the island from the 1960's and 1980's. Thus, the high vulnerability index for the southern tip of the island, where there is a major village, is based upon the low gradient of the coast, the general absence of coastal vegetation, because of clearing the presence of some minor sea wall constructions, and the fact that there has been shoreline recession in this area between aerial photographic runs. Some of the recession along this shoreline may have been related to the building of the causeway and bridge linking this island with Bonriki to the south.

TABLE 2. NATURAL SYSTEM DATA: BUOTA

	Buota	Naninimai	Total
Upper shore			
sand	5800 m	100 m	5900 m
shingle	100 m	700 m	800 m
sand and shingle	100 m	--	100 m
Lower shore			
conglomerate platform	600 m	500 m	1100 m
conglomerate ramp	500 m	--	500 m
conglomerate outcrop	60 m	--	60 m
beachrock	120 m	--	120 m
mangrove	2100 m	--	2100 m

FIGURE 8. VULNERABILITY INDEX, BUOTA



LIMITATIONS TO THE APPLICATION OF THE IPCC COMMON METHODOLOGY TO KIRIBATI

For the Republic of Kiribati, much of the fundamental data required for the IPCC Common Methodology are not readily available. Details of land use, land capability, natural vegetation distribution, sediment type, agricultural production, etc., are not stored in any central retrievable system. There is generally little or no information on elevation, which is particularly important in assessing vulnerability to accelerated sea level rise.

There is very little information on the natural dynamics of the shoreline. Kiribati lies in a part of the Pacific affected by El Niño, which accounts for major variations in climate factors and water levels. There is no information on rates of sediment production, patterns of sediment movement, or rates of sediment deposition. In view of the dynamic nature of the shoreline, it is not possible to calculate areas of land that will be lost—or, indeed, areas that might be gained—under conditions of sea level rise. It is clear that the shoreline will continue to change, regardless of whether the sea rises, falls, or remains stable. Reef scientists are divided in their view of the most likely effect of sea level rise on reef islands.

The Kiribati economy combines a limited cash economy with a traditional subsistence economy and substantial international aid. It is not possible to assess these three elements within the benefit/cost framework proposed in the methodology. Furthermore, there are a whole range of extremely important social, political, and cultural factors that are likely to be affected by a rise in sea level, but of which no account can be taken within the format of the Common Methodology. These factors may be of minor importance for many other nations for whom a rise in sea level means inundation of some expensive real estate around the periphery of a large nation, but they are important to the way of life of the entire population of Kiribati, which lives very close to, and only a little above, the sea.

It is clear that total protection, as is suggested as one scenario in the IPCC Common Methodology, is not a viable option for a nation such as Kiribati, where the perimeter is extremely large, but the total area very small. Even total protection of one or two islands could only be undertaken on receipt of aid from overseas, and financial and economic constraints will be the most critical impediments to the implementation of any response strategy.

CONCLUSIONS

Kiribati (together with the other small coral atoll states) is the most vulnerable of nations to anticipated sea level rise. Its population lives in a delicate balance with the sea, and accelerated sea level rise would have an impact on every facet of life in Kiribati. The rational economic approach advocated in the IPCC Common Methodology takes no account of these social, political, and cultural factors, nor can it be adequately applied to the interlocked cash/subsistence economies of Kiribati.

Although the potential consequences of sea level rise remain uncertain, water-level reconstructions for Kiribati from tidal stations and from intertidal corals suggest that the present situation is not one of immediate crisis, but that there is time to undertake monitoring and research to establish the rates of sea level rise actually in, and relative to, Kiribati, and the response of reef islands to water-level changes.

There is a need to gather more basic environmental data on the distribution of the nation's natural resources: vegetation, sediments, soils, water quality, and land use. These data are needed to provide an essential baseline study for the country as a whole, for it will only be through such monitoring that it can be accurately assessed what resources are lost (or gained) in the future. The data will be valuable for many environmental planning purposes, in addition to planning for coping with sea level rise. The aerial photographic coverage already available in Tarawa would provide a good starting point, and mapping would require a minimum of technical expertise.

Research needs to be conducted on sediment production, transport, and deposition. Techniques should involve investigation of the geological and geomorphological history of several islands, and regular monitoring of beach/shoreline profiles (along the lines of the twice-yearly surveys of Betio and Bairiki, but including areas remote from human disturbance and causeways) to gauge natural processes of accretion and erosion (expertise for such monitoring already exists in Tarawa).

Shoreline vulnerability analysis needs to be combined with coastal zone mapping. In view of the inevitable shortage of resources in the Environment Section of the Ministry of Environment and Natural Resources Development, Kiribati, coastal zone mapping should probably be undertaken as a part of the broader land resources study suggested above. Coastal types should be determined in a manner somewhat similar to that attempted for Buota in the case study above (see Figure 7). This should then allow determination of a vulnerability index, as has been attempted for Buota (see Figure 8). This vulnerability indexing of the coast is intended as a planning and management tool for the present coast, to regulate building setback distances from the high-water mark, to demarcate certain beaches from which no sediment should be collected, or to protect a stretch of coastal vegetation. This would also then serve to indicate vulnerability to accelerated sea level rise.

To meet these objectives, the recently established environment section of the Ministry of Environment and Natural Resource Development will be dependent on some help from the international community.

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ASSESSMENT OF THE VULNERABILITY OF MAJURO ATOLL TO SEA LEVEL RISE

Martha Crawford
Environmental Protection Authority
Republic of the Marshall Islands

Paul Holthus
South Pacific Regional Environment Programme

Clary Makroro
Office of Planning and Statistics
Republic of the Marshall Islands

Eiji Nakasaki and
Scott Sullivan
Sea Engineering, Inc.

SUMMARY

INTRODUCTION

This report is the result of a 6-month study funded by the U.S. National Oceanic and Atmospheric Administration (NOAA) on the potential vulnerability of the Republic of the Marshall Islands to selected future accelerated sea level rise scenarios and a preliminary view of possible adaptive response options should such scenarios become reality.

The scenarios and the methodology used in this study come from the Coastal Zone Management Subgroup of the Intergovernmental Panel on Climate Change - Working Group III Response Strategies (IPCC). The Majuro Atoll case study is one of approximately 25 case studies being conducted around the world under the auspices of the IPCC and, as such, provides valuable information for IPCC assessments being conducted on Global Climate Change.

The objective of this study is threefold: (1) to assess the potential effects of accelerated sea level rise (ASLR) on the Republic of the Marshall Islands, as represented by Majuro Atoll; (2) to identify possible response strategies that would minimize the effects of ASLR; and (3) to analyze Majuro's vulnerability *viz-a-viz* its ability to implement selected response options and what types of future assistance might be required to reduce vulnerability. The purpose of the study is provide information that can be used by the government of the Republic of the Marshall Islands (hereinafter "Marshall Islands") for *conceptual* planning purposes only with respect to future sea level rise scenarios, and to provide information to the Intergovernmental Panel on Climate Change (IPCC) for its assessments of global climate change.

This report summarizes the results of a larger report and has been prepared to satisfy the requirement of the IPCC-CZMS for report preparation, and to provide a more condensed version for the Marshall Islands to satisfy their purpose in disseminating the report.

ANALYTICAL METHODOLOGY

This case study follows a methodology developed by the IPCC Coastal Zone Management Sub-Group entitled: "The Seven Steps to the Assessment of the Vulnerability of Coastal Areas to Sea Level Rise: A Common Methodology," September 1991 (Common Methodology), the objectives of which are identified above. Funding for the study was provided by the U.S.

National Oceanic and Atmospheric Administration (NOAA) to the South Pacific Regional Environmental Programme (SPREP) to coordinate the substantive work and document preparation.

LIMITS AND ASSUMPTIONS

This case study covers the effects of accelerated sea level rise (ASLR) and the boundary conditions provided in the Common Methodology, i.e. 1 foot (0.3 meters) and 3.3 feet (1.0 meter) by the year 2100. The study does not consider other aspects of climate change—e.g. increased frequency and intensity of extreme events (note: with ASLR, smaller storms may increase the frequency of flooding events but without the wind speeds of larger storms), changes in temperature and rainfall patterns, etc. Because adequate data or predictive models are not available at this time, tectonic movement and subsidence, which would affect the relative rise in sea level, have not been taken into account, although these factors may not be inconsequential and could later be considered through sensitivity analysis.

The oceanographic and engineering aspects rely on existing data for prediction of wave and water level conditions. Limited topographic and bathymetric information in particular has required that assumptions and extrapolations be made for land levels and bottom profiles. Social and economic descriptions and predictions rely on existing data and speculate on future growth and development for purposes of scenario development only.

The ecological aspects of the case study focus more on the shoreline and shallow reef environment, due to the importance of these areas to responses to ASLR response. Also, the terrestrial environment, when not modified by man, is generally similar through out Majuro Atoll. It has not been possible to factor in the response of coral reefs and reef/shore sediment budgets as part of this case study. It is assumed that coral reef growth will "keep up" with the ASLR boundary conditions given in the Common Methodology if they have not been stressed by human or natural activities, thereby providing a greater level of natural protection. Because this criterion is not factored into the study, the estimates of future impacts may be greater than might actually occur. Data are presented in the form available, usually not in metric units.

TOPOGRAPHIC AND BATHYMETRIC INFORMATION BASE

Topographic and bathymetric data are essential to undertaking a study on the effects of sea level rise and determine the level of detail and approach for much of the study's work. This kind of information is not available for most atolls, and the Marshall Islands are no exception. Detailed information even for Majuro Atoll is limited, with detailed topographic data available only for Study Area 1 (D-U-D area) and for the airport area (Study Area 3). For other study areas qualitative shoreline profile data were obtained.

The topographic and bathymetric data were:

- Topographic maps (1"=40') for the D-U-D area (Study Area 1) with 1-foot contours (Surveyed in 1983).
- Majuro airfield and related facilities plan maps (1986).
- A 1:35,000-scale hydrographic map for Majuro Atoll issued by the Defense Mapping Agency Hydrographic Center, USA.

- Majuro Atoll Coastal Resource Atlas (Manoa Mapworks, 1989).
- Bathymetric data near the west end of the old runway, surveyed by Sea Engineering, Inc. (1983).

Due to the lack of bathymetric information, ocean-side bottom profiles are considered to have relatively uniform characteristics, with a reef elevation at about mean low-water level, and a steep slope seaward of the reef edge. A model profile was made, using the existing bathymetric data near the west end of the old runway (Sea Engineering, Inc., 1983). Reef widths in Study Areas 1, 2, and 3 were estimated using aerial photos in the Majuro Atoll Coastal Resource Atlas. Lagoon-side bottom profiles were approximated using bathymetric data from the 1:35,000 scale hydrographic map and measuring reef widths on aerial photos.

SHORELINE CHARACTERISTICS

A field inventory of the study area shorelines documented characteristics, composition, damage, existing erosion or accretion, and erosion potential. The location, characteristics, and general condition of the shoreline structures were noted.

CLIMATIC AND OCEANOGRAPHIC PARAMETERS AND ASLR IMPACTS

Shoreline inundation limits and shore protection design parameters were determined for the study areas using climatic, oceanographic, and topographic data available for Majuro Atoll and the profiles obtained. Parameters determined include wave heights, water levels, and run-up elevations for estimated 2-year, 50-year, and typhoon events for present-day sea level and ASLR.

ALTERNATIVE SHORE-PROTECTION MEASURES

General methods and techniques for shore protection, erosion control, and flood protection were evaluated, including advantages and disadvantages, design and construction requirements, level of protection, construction material considerations, and applicability to the study area.

ECOLOGICAL INVESTIGATIONS

Description and assessment of the existing terrestrial, shoreline, and nearshore resources and environmental conditions were based on the Majuro Coastal Resources Atlas (Manoa Mapworks, 1989), the coastal resource inventory which was undertaken as a basis for the Atlas (in draft form only), and the RMI State of the Environment report (Crawford, 1992). Additionally, more detailed information was gathered through field investigations in each of the study areas. This included shoreline surveys and rapid ecological inventories of nearshore reef areas.

SOCIOECONOMIC INVESTIGATIONS

Socioeconomic investigations were based on statistics published by the Office of Planning and Statistics in the first and second Five Year Development Plans (OPS, 1986 and 1991c), Statistical Abstracts 1988/89 and 1989/90 (OPS, 1989b and 1991c), and the National Population Policy ((OPS, 1991a). This information provided the basis for describing the social and economic situation, projecting a future development scenario, analyzing potential social and economic impacts, and determining response strategies.

PRINCIPAL FINDINGS

Because of the potentially serious implications of ASLR to the already vulnerable atolls and islets of the Marshall Islands, a needs assessment with an interest toward strengthening the nation's capabilities in dealing with sea level rise indicates several areas that should be addressed. The study was based mostly on existing information that in many cases required making assumptions. There is a need for improved baseline data, such as topographic and bathymetric maps, aerial surveys, historical erosion rate maps, and satellite imagery needed to project physical impacts and to monitor changes. Some long-term studies are needed to establish a time-series data base for comparative and analytical purposes.

Additional socioeconomic studies are needed as well to better understand such things as changes in traditional land-use (both to land-tenure system and the loss of agricultural land to urban use), housing needs to satisfy increasing population growth (e.g., will multistory structures be built, and how should they be built to minimize hazards of flooding and erosion), and how to encourage and attract future growth and development (tourism, etc.) in areas considered to be at risk?

Needs that will necessitate attention in both the short and the long runs will include increased funding to finance better protection measures. For example, specific planning measures should be undertaken to consider selected elevation of islands and defensive structures built to withstand design storms. Given the high cost of construction (including materials that may have to be imported) in relation to the overall small gross domestic product (GDP) of the country, long-term capital improvement planning and acquisition of funding (internally and from outside sources) will be required to provide adequate protection for at least the most important and highly developed parts of the island.

Increased regional cooperation, aimed at sharing technology and experiences, will also be required. Global climate change models may not be the best source of predictors for sea level rise in the Pacific, so sharing the benefits of more specific and improved models will provide even better information on which to make future decisions. Better state-of-the-art tidal gauges and global monitoring initiatives will provide greater certainty to the areas that are now speculated on.

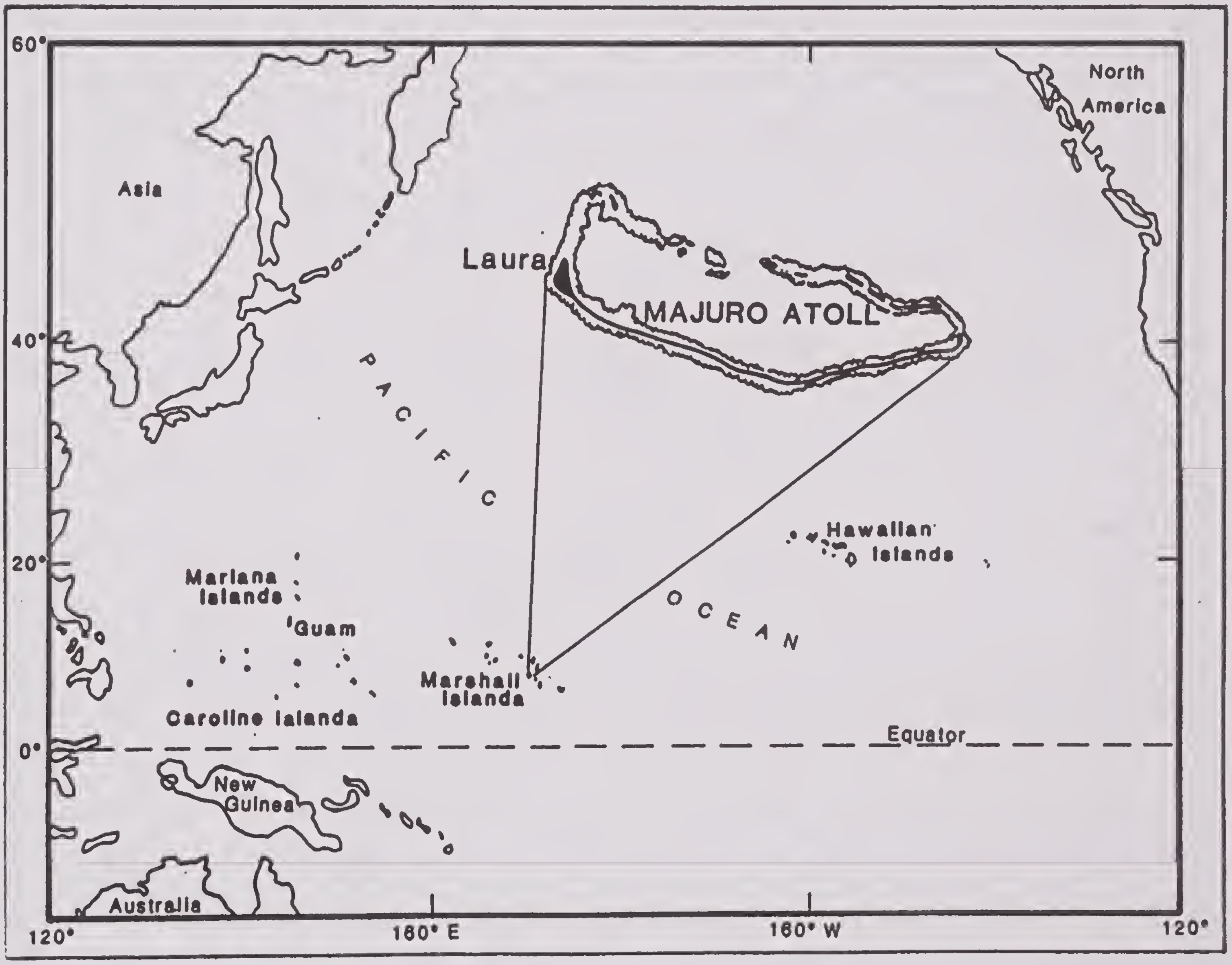
While the most severe impacts of ASLR would not start to be noticed for 20 or 30 years, largely depending on the rate of rise, some institutional changes should be considered now. Institutional strengthening will be required to equip the present institutions to deal with the new challenges of sea level rise. Coastal zone management planning (to include natural hazards planning) is needed to help minimize existing flooding and coastal erosion problems and plan for future events. Development and implementation of the existing coastal zone management legislation would provide one of the best adaptive measures and should be undertaken as soon as possible.

DELINEATION OF STUDY AREA AND SPECIFICATION OF ASLR SCENARIOS

STUDY AREA LOCATION

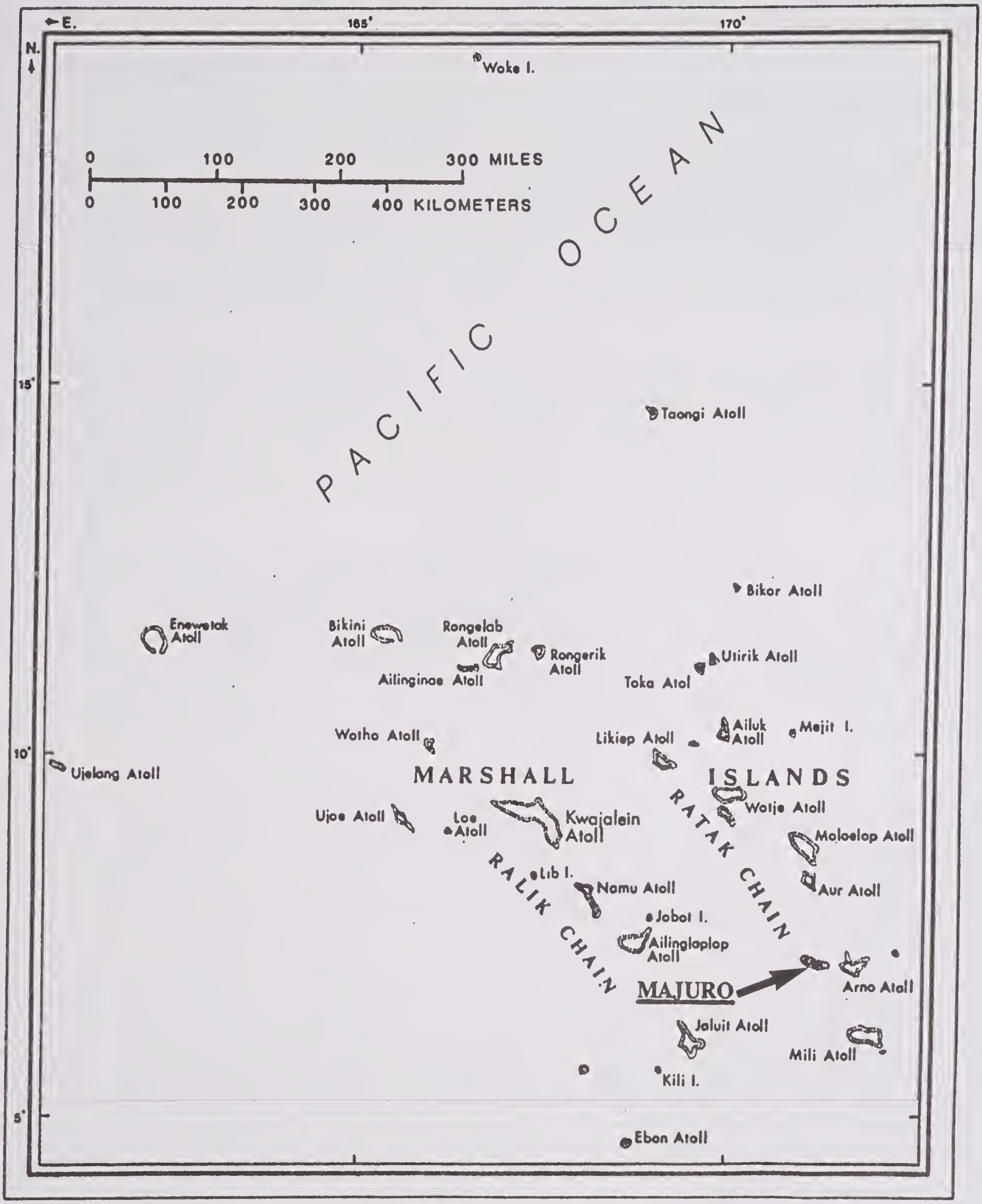
The Marshall Islands consist of 34 atolls and islands totaling about 70 square miles (sq. mi.) and divided into two chains located in the West Central Pacific Ocean (Figure 1). The atolls and islands enclose about 4,037 sq. mi. of lagoon area. The Exclusive Economic Zone (EEZ) encompasses about 750,000 sq. mi. of ocean.

FIGURE 1. THE MARSHALL ISLANDS



This case study focuses on Majuro Atoll, the capital island of the Republic of the Marshall Islands, which is at latitude 7°N and longitude 171°E, near the southern end of the Ratak (eastern) chain of the Marshall Islands (Figure 2).

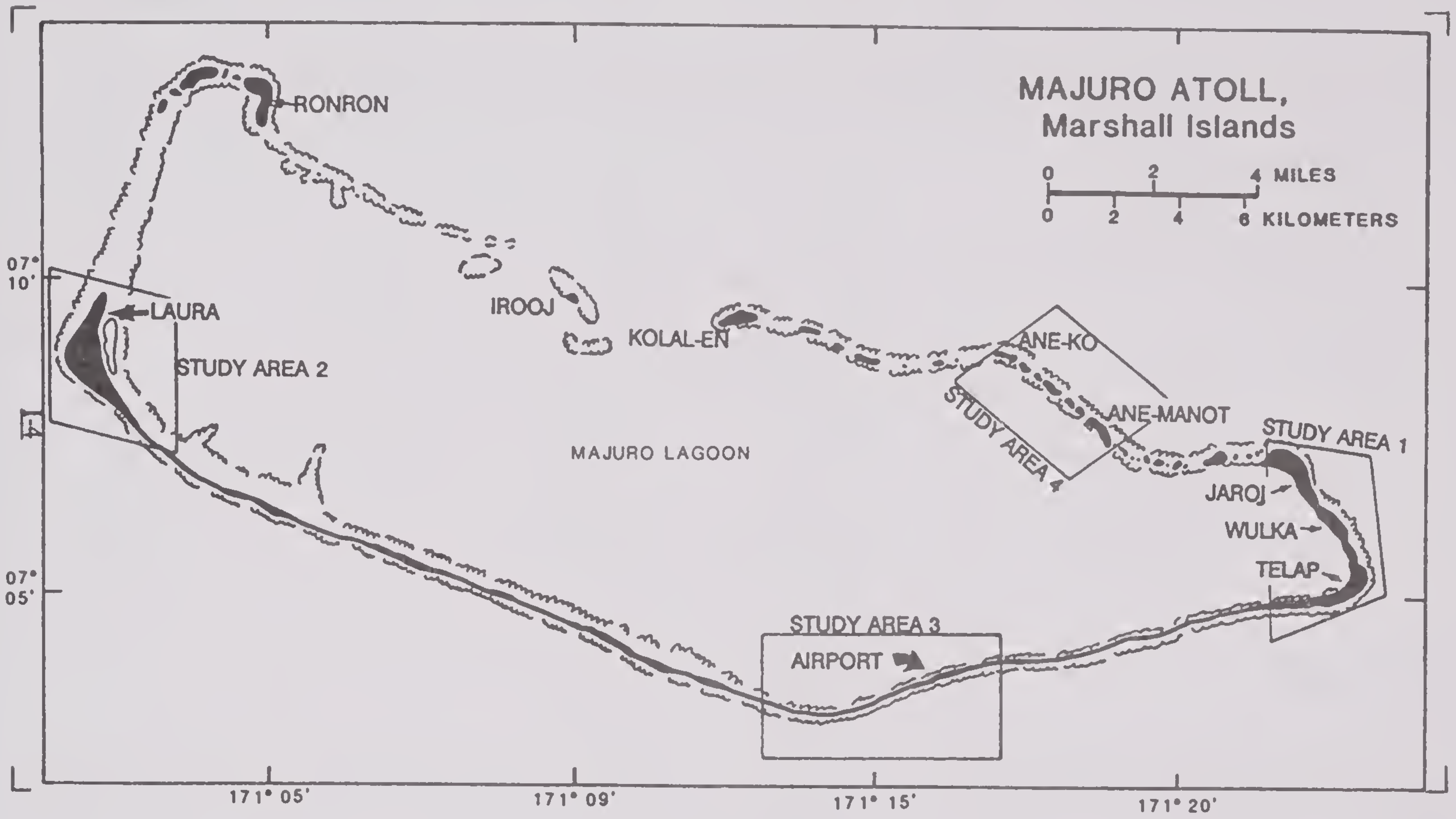
FIGURE 2. LOCATION OF MAJURO ATOLL IN RELATION TO OTHER ISLANDS



Majuro atoll is a typical atoll, composed of a ring-shaped reef system enclosing a saltwater lagoon. The elongated atoll is 25 miles from east to west and 6 miles from north to south (Figure 3). The 64 low islets of the atoll vary in width, from about 0.1 to 0.5 miles. The land area is about

4 sq. mi., and the average land elevation is less than 8 feet. The lagoon has a surface area of about 125 sq. mi., and an average depth of about 150 feet, descending to a maximum depth of 220 feet.

FIGURE 3. MAJURO ATOLL AND LAGOON



The major deep passes into Majuro Lagoon occur along a 7-mile stretch of the northeastern side of the atoll. Most of the land is distributed along the southern and western sides. The islets of the eastern end of Majuro have been joined by causeways to make a single land mass.

Due to the large size of Majuro Atoll, four study areas were selected to represent the atoll. These are representative of typical portions of many atolls of the Pacific. For each of the study areas, there was no need to define an inland boundary due to the low-lying and narrow characteristics of the land unique to atolls. The seaward boundary was the bottom of the ocean reef slope and the waters immediately surrounding the atoll, to an arbitrary distance offshore of 100 meters. The lagoon-ward boundary was the bottom of the lagoon side reef slope, when it reached average lagoon depths, and the overlying waters. Selected "impact zones" were determined when identifying loss of dry land and flooding events (distance inland).

General characteristics of the study areas are listed in Table 1.

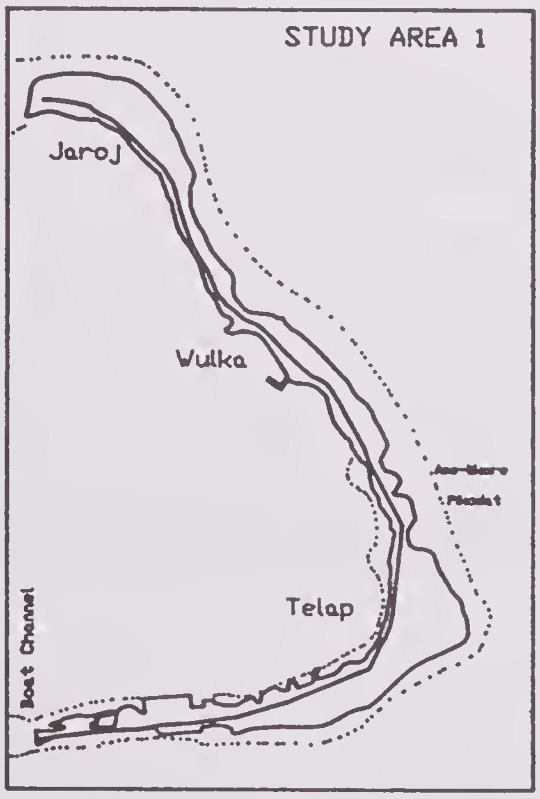
TABLE 1. STUDY AREA CHARACTERISTICS

	Area 1	Area 2	Area 3	Area 4
Land area (sq mi) (acres)	0.8	1.2	0.4	0.2
Land length (mi)	510	770	255	130
	4.71	2.3	5.0	2.6
Shoreline length				
Lagoon (mi)	4.8	2.5	5.0	2.5
Ocean (mi)	5.6	3.3	5.0	3.8
Landwidth (ft)				
Minimum	330	660	165	165
Maximum	1,980	4,290	825	660
Reef flat area (sq mi) (acres)	0.8	1.2	0.5	0.7
	510	770	320	450
Reef flat width				
Lagoon				
- Minimum	10	990	165	165
- Maximum	660	1,980	330	825
Ocean				
- Minimum	165	330	165	330
- Maximum	825	2,310	660	660

STUDY AREA 1

The Jaroj-Wulka-Telap area (Figure 4), also commonly known as Dalap-Uliga-Darrit, or just D-U-D, is the commercial and population center of Majuro Atoll. Most of the facilities and the principal settlement are in this area. Of the 19,600 people living on Majuro, about 14,600 live in this area.

FIGURE 4. STUDY AREA 1

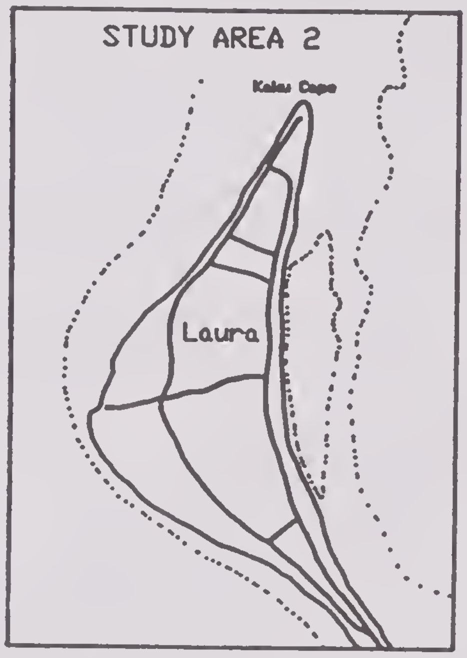


The area was chosen to represent the urban atoll setting with high-density human habitation. These atoll areas have major infrastructure development, significant shoreline alteration, largely degraded land and reef resources, and are the location of government, commerce, transportation, and telecommunications.

STUDY AREA 2

The Laura area (Figure 5) is the largest island of Majuro Atoll and has important ground-water resources. The land area is about equal to that of Study Area 1, but has fewer than 2,000 people.

FIGURE 5. STUDY AREA 2



This area was chosen to represent a primarily rural atoll setting, which makes up the vast majority of the atoll land areas of the Pacific. These areas have little infrastructure development or shoreline alteration, low population density, and terrestrial and marine habitats that are not significantly degraded. They often have important ground-water and agricultural resources.

STUDY AREA 3

This long, narrow area (Figure 6) extends along the south side of the atoll, a large portion of which consists of the airport causeways connecting the islets. This area was chosen to represent the long and narrow land areas that are common on typical atolls. In addition, the area contains the airport which is an essential part of modern atoll and infrastructure, and is usually constructed along these long narrow portions of atoll islets.

STUDY AREA 4

This chain of islets, Ane-ko to Ane-manot, at the NE end of Majuro Atoll contains about 10 small islets (Figure 7). The islets are separated from each other by short distances on the reef flat that are generally awash at all but low tide. This area was chosen to represent the many portions of atolls that consist of a series of small islets. These are usually not permanently inhabited, but serve as a base for the use of terrestrial and marine resources in the area.

FIGURE 6. STUDY AREA 3

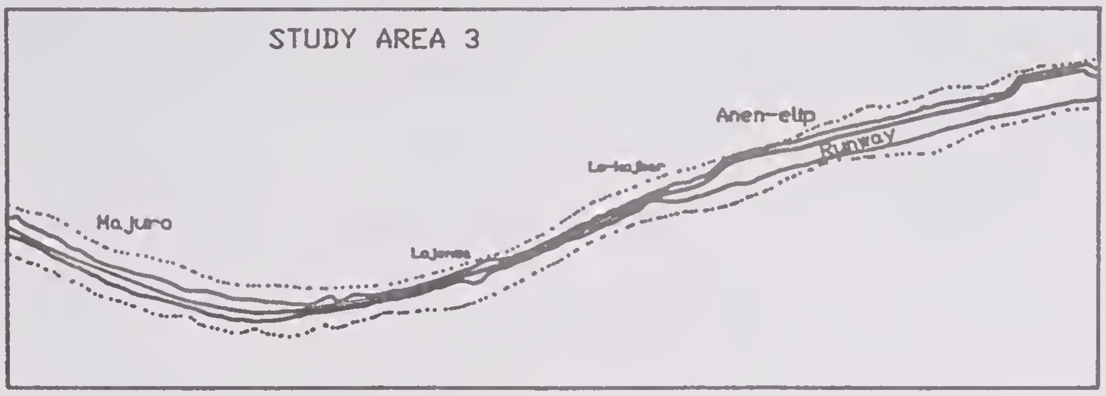
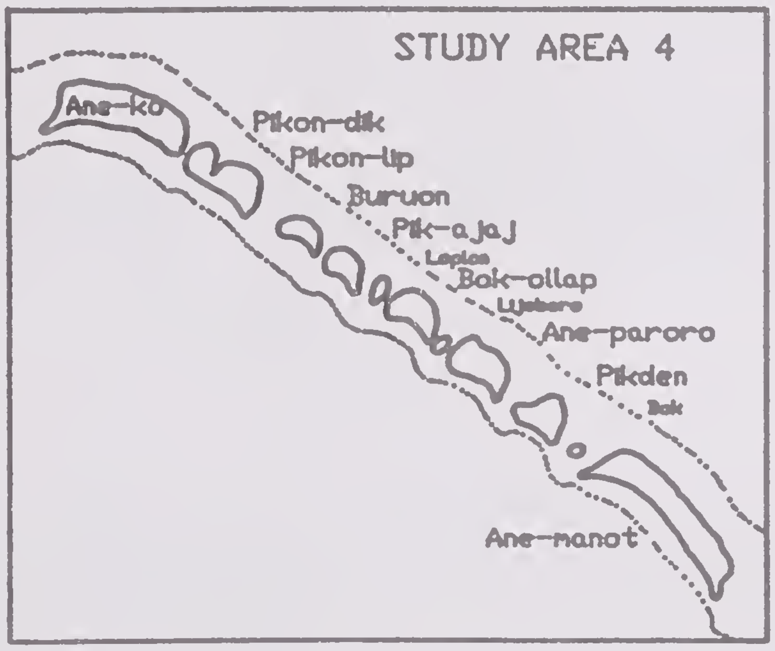


FIGURE 7. STUDY AREA 4



CLIMATOLOGICAL FACTORS

Climate will have a large influence on the overall effects of sea level rise. Wind, waves and storm events must be considered in the delineation of impact areas, as well as developing response strategies.

GENERAL CLIMATE

Northeasterly tradewinds are the prevailing winds at Majuro Atoll, averaging approximately 10 knots 80 percent of the time. The tradewinds predominate from December to April with moderate wind speeds, and become weaker and are less steady in the summer and fall months.

Rainfall at Majuro Atoll averages about 140 inches annually, however periods of drought are not unknown. Summer and fall are normally the wettest seasons, and winter and spring are dry. Temperatures are relatively constant throughout the year, with mean monthly temperatures ranging one degree (81°– 82°F) between the coolest and warmest months.

Severe storms with damaging winds are infrequent near Majuro Atoll, although typhoons can occur in the vicinity. A major storm in 1918 resulted in the loss of many lives at a time when the population numbered only 1,400. Tropical disturbances tend to originate in the region and move from east to west.

WINDS

The annual extreme wind speed is estimated to be 34 mph, and the 50-year wind is 47 mph (Table 2). During the storm of January 1992, peak wind speeds were estimated to be 60 mph.

TABLE 2. THE PREDICTED WIND SPEED AT MAJURO ATOLL AS A FUNCTION OF RETURN PERIOD

Return Period (years)	Fastest-Mile Wind Speed (mph)
2	34
10	37
25	45
50	47

Source: U.S. Weather Bureau data.

WAVES

Majuro Atoll is exposed to sea and swell generated from nearly all directions. The primary wave types affecting the atoll are: (1) the prevailing easterly tradewind waves, (2) south and north Pacific swell, and (3) waves generated by tropical storms and typhoons.

Tradewind waves may be present throughout the year, and are highest from December through April. They result from the steady tradewinds blowing from the east-northeast over open ocean. Typically, the deep-water tradewind waves have periods of 5 to 8 seconds and heights of less than 6 feet.

South and North Pacific swell is generated during the winter in each hemisphere. South swell is generally characterized by long, low waves approaching from the southeast through southwest, with periods of 12 to 20 seconds and deep-water wave heights of 2 to 6 feet. North Pacific swells typically has periods of 10 to 16 seconds and heights of 5 to 15 feet. No quantitative data is available regarding the characteristics and frequency of South and North Pacific swell affecting Majuro. Long-period ocean swells can considerably damage atolls because of their potential for wave run-up and overtopping of the land area. This does not often occur, suggesting that severe north and south swells are not frequent. The predicted significant wave height for Majuro Atoll used for the analysis is shown in Table 3.

TABLE 3. PREDICTED SIGNIFICANT WAVE HEIGHT FOR MAJURO ATOLL AS A FUNCTION OF RETURN PERIOD

Return Period (years)	Significant Wave Height (feet)
2	13
10	16
25	17
50	19

Source: Summary of Synoptic Meteorological Observation Data.

TROPICAL CYCLONES

Tropical cyclones near the Marshall Islands are generally in their formation stage and rarely reach typhoon strength until they have moved west. No storm with typhoon strength has hit Majuro Atoll for over 30 years.

Historical records of tropical cyclones show that during the 15-year period from 1974 to 198, only two tropical storms and no typhoon approached Majuro within 150 nautical miles. The maximum fastest mile wind speed recorded at Majuro from 1958 to 1990 was 47 mph, or 41 knots, well below typhoon strength of 64 knots. However, a tropical storm hit Majuro in January 1992, with peak winds of 55–60 mph (48–52 knots). Four tropical storms and two typhoons passed within 150 nautical miles of Kwajalein (220 nautical miles NW of Majuro) during 1974–1988. It is reasonable to consider that there is currently a potential typhoon threat at Majuro Atoll, but perhaps even more so should atmospheric warming change storm patterns.

TIDES

The tides at Majuro Atoll are semidiurnal, with pronounced diurnal inequalities (i.e., two tidal cycles per day of unequal tidal range). Predicted mean range and mean spring range at Majuro Atoll are 3.7 and 5.3 feet. A highest tidal level observed at Majuro in 1977 was 6.8 feet above the datum or 3.6 above mean sea level (MSL).

SPECIFICATION OF ASLR SCENARIOS

ACCELERATED SEA LEVEL RISE (ASLR)

Three scenarios of future sea level rises were considered: (1) no sea level rise, (2) ASLR1 = 0.3 (1.0-ft) rise, and (3) ASLR2 = 1.0 (3.30-ft) rise, as specified in the Common Methodology.

DESIGN WAVES

Majuro Atoll is subject to waves generated by tropical storms or typhoons passing through the Marshall Islands, but not necessarily passing directly over the atoll. The average annual fastest-mile wind speed is 35 mph (below the 39 mph threshold for tropical storms). Waves generated by strong winds in these nearby storms are considered to represent wave design conditions with a probable chance of occurrence in Majuro. The potential for a typhoon to directly strike Majuro is low and represents worst-case design wave conditions. Nevertheless, it should be taken into consideration, as it would cause the greatest destruction.

Based on historic data, three wave conditions were analyzed to assess shoreline vulnerability and evaluate the need for shore-protection improvements:

- *2-year Event*—representing annual conditions
- *50-year Event*—representing probable extreme conditions
- *Typhoon Event*—representing worst case conditions

For comparison, the January 1992 storm was more severe than the 50-year event, but significantly less severe than the typhoon event.

The actual probability of any of the three cases directly striking any specific site of the study areas is less likely than indicated by the estimated return periods, due to the variability in directions of winds and waves. Thus, the analysis and results are conservative but represent reasonable general planning and design guidelines for assessing shore-protection problems and needs.

Table 4 identifies the deep-water design wave heights which are used for estimating impacts and shore-protection design criteria.

TABLE 4. DEEP-WATER DESIGN WAVE HEIGHTS (H_S, FEET) AND PERIODS (T, SEC)

	Fetch (n.m)/ Depth (ft)	**Annual Wave**		**50-year Wave**		**Typhoon Wave**	
		H_S	T	H_S	T	H_S	T
Ocean Side							
All Areas	N/A	13	13	19	13	27	11
Lagoon Side							
Study Area							
1 & 2	21/140	6	5	8	6	19	8
3 & 4	6/140	3	4	4	4	11	5

RISE IN STILL-WATER LEVEL

An important step in determining storm inundation limits and wave runup elevations is estimating the rise of the level of still water. This rise along the shoreline during extreme wind and wave events is generally a function of three components: (1) the astronomical tide, (2) storm surge due to reduced atmospheric pressure and wind stress setup, and (3) wave setup.

The rise in still water caused by these components listed above is considered in conjunction with a tide level of +2.6 feet above mean sea level (equal to mean high water) due to its frequency of occurrence.

The total rises in water levels along study area shorelines are summarized for each ASLR value in Table 5. Study Area 4 is not a continuous coastline, but rather a group of islets. Water pushed up into this area can flow between the islets, thereby reducing setup.

TABLE 5. STILL-WATER LEVEL RISE COMPONENTS
(IN FEET ABOVE MSL)

A. OCEAN SIDE ASLR= 0

	Annual Extreme	*50-Year Extreme*	*Typhoon Event*
Study Area 1	4.9	6.0	8.3
Study Area 2	4.9	6.0	8.3
Study Area 3	4.9	6.0	8.3
Runway section	4.4	5.5	7.8
Study Area 4	3.9	4.5	6.3

B. OCEAN SIDE ASLR= 1.0 FOOT

	Annual Extreme	*50-Year Extreme*	*Typhoon Event*
Study Area 1	5.7	7.0	9.3
Study Area 2	5.7	7.0	9.3
Study Area 3	5.7	7.0	9.3
Runway section	5.3	6.4	8.6
Study Area 4	4.9	5.3	6.9

C. OCEAN SIDE ASLR= 3.3 FEET

	Annual Extreme	*50-Year Extreme*	*Typhoon Event*
Study Area 1	7.8	9.0	11.3
Study Area 2	7.8	9.0	11.3
Study Area 3	7.8	9.0	11.3
Runway section	7.3	8.3	10.4
Study Area 4	6.8	7.3	9.0

D. LAGOON SIDE ASLR = 0

	Annual Extreme	*50-Year Extreme*	*Typhoon Event*
Study Area 1	3.6	4.1	7.7
Study Area 2	3.6	4.1	7.7
Study Area 3	3.0	3.3	5.7
Study Area 4	2.9	3.0	4.9

E. LAGOON SIDE ASLR = 1.0 FOOT

	Annual Extreme	*50-Year Extreme*	*Typhoon Event*
Study Area 1	4.5	5.0	8.6
Study Area 2	4.6	5.1	8.6
Study Area 3	4.0	4.3	6.6
Study Area 4	3.9	4.0	5.7

F. LAGOON SIDE ASLR = 3.3 FEET

	Annual Extreme	*50-Year Extreme*	*Typhoon Event*
Study Area 1	6.5	7.1	10.6
Study Area 2	6.7	7.2	10.8
Study Area 3	6.2	6.4	8.6
Study Area 4	6.2	6.3	7.9

NATURAL CHARACTERISTICS OF THE STUDY AREA

MARSHALL ISLANDS

GEOMORPHOLOGY

The Marshalls Islands consist of a series of mid-ocean reef platforms rising from ocean depths of more than 5,000 feet, which form atolls and reef islands. Atolls are ring-shaped reef features enclosing a central lagoon, which averages about 150 feet in depth, with a series of low-lying islets positioned around the ring reef. Reef islands are low-lying islets positioned on a reef platform, without a central depression or lagoon.

The land area is built of reef-derived sediments (coral and calcareous algae debris, formanifera, molluscs) of different sizes (sand, gravel, rubble, block) deposited onto the shallow reef platform. The shoreline is often fronted by a ramp of beach rock and/or slightly raised platform of conglomerate rock. The adjacent reef flat is generally a solid reef surface that is exposed at low tide.

Land area in the Marshall Islands is generally flat, rarely reaching over 10 feet in elevation, with the oceanside storm-deposit beach berms forming the highest points. Soils are very poor and consist of calcareous sediment, with limited organic input from the island vegetation. The soil is very porous with high salinity due to salt spray and high evaporation rates.

Larger land areas support a lens of fresh water, which floats on and mixes with the denser sea water permeating the carbonate sediments and structure below the islet. The lens depends on recharge by rainwater, as there is no surface runoff on the porous land mass, and is affected by the size and shape of the island and tidal fluctuations.

TERRESTRIAL FLORA

Atoll plant communities are relatively low in species number. Most of the original vegetation of the Marshall Islands has been replaced by coconut plantations. There are some small native forest species on the fringes of some of the islets. Portions of the interior of larger islets have been excavated to form shallow freshwater pits where taro, a staple root crop, is cultivated. Shoreline areas support typical beach strand vegetation, which is common throughout the Pacific. There is little information that the Marshall Islands contain unique, endemic, rare, or endangered plant species.

TERRESTRIAL FAUNA

As with most atolls of the Pacific, the Marshall Islands are species poor in land fauna. The Polynesian rat, the only land mammal native to the Marshall Islands, arrived with prehistoric Pacific voyagers. Information on the reptile fauna indicate 7 species of lizard and 1 species of blind snake, none of which is endemic to the Marshall Islands. There is virtually no information on the terrestrial invertebrates of the Marshall Islands. The coconut crab is widespread, although declining in abundance on inhabited atolls due to its popularity as a food item.

AVIFAUNA

Some 70 bird species have been reported from the Marshall Islands. Of these, 39 are land or freshwater birds that inhabit the country for part of the year or are migratory. No endemic species or passerine species are known from the Marshall Islands, however two native forest birds are rare. One of these may be extinct, and the other is classified as endangered. Seabirds form an important part of the avifauna of the Marshall Islands, with 15 species nesting and breeding, primarily in the northern atolls.

MARINE FLORA

The marine flora are a subset of higher diversity communities further to the west. Only a few of the southern, wetter atolls in the Marshall Islands have small mangrove stands. Sea grass beds are relatively rare, with limited areas on a few atolls. The algae of the Marshall Islands are relatively well known, with 238 species of green, brown, red and blue-green algae recorded.

MARINE FAUNA

As with flora, there is little marine fauna that is unique or endemic to the Marshall Islands. Coral reef surveys have documented relatively high diversity of reef corals, with 180 coral species from 60 genera in the southern Marshall Islands. Coral reef diversity also includes the diverse assemblage of sponges, clams, oysters, mussels, gastropods, tunicates, worms, crabs, shrimps, sea cucumbers, and starfish. These include many species that are important for subsistence and potential commercial use. Giant clam stocks are declining, as elsewhere in the Pacific.

The Marshall Islands marine environment contains over 250 species of reef fish from 50 families, most of which are used as food sources. Pelagic species, particularly tuna, are also abundant and have important commercial value.

The world's 5 marine turtle species all occur in the Marshall Islands. The Hawksbill and Green turtle both nest in the country; the former is rare and endangered. As many as 27 species of whales, dolphins and porpoises occur in Marshall Islands waters.

SPECIAL ECOLOGICAL AREAS

Whiles there are no "special ecological areas" such as national parks or nature reserves in the Marshall Islands, many areas deserve consideration. There is international conservation interest in several northern atolls due to their nesting seabird and marine turtle populations.

MAJURO ATOLL

Majuro Atoll generally represents the typical atoll natural systems described for the Marshall Islands as a whole. This includes typical geomorphology, soil, and hydrologic conditions.

Majuro has terrestrial flora and fauna typical of the Marshall Islands and atolls in general. These have been much disturbed by the high level of human habitation and development in parts of the island. There are no major seabird breeding colonies on Majuro, although seabird sites exist along the islets to the north.

The marine flora and fauna of Majuro Atoll are generally typical. A total of 146 species of corals from 50 genera and subgenera have been recorded at the atoll. There is little mangrove at Majuro. While many turtles frequent the area, there are no major marine turtle nesting or breeding areas at Majuro Atoll.

The Coastal Resource Atlas indicates there is a marine park along the lagoon side of Study Area 4 along with numerous "tourism sites" scattered throughout the atoll. There are also many archeological, historic and cultural sites throughout. There are no identified rare or endangered species known to occur on Majuro that might be affected by ASLR.

The natural systems of each of the four study areas are described in more detail below, and in Table 1.

TABLE 6. NATURAL SYSTEM CHARACTERISTICS

Natural Systems	**Marshall Islands**	**Majuro**	**Area 1**	**Area 2**	**Area 3**	**Area 4**
Water Resources	N/A	N/A	none	major aquifer	runway catchment	none
Terrestrial flora & fauna	Typical of mid-Pacific atolls	Typical of Marshall Islands	Typical of Majuro	Typical of Majuro	Typical of Majuro	Typical of Majuro
Avifauna (# of species)	70	?	?	?	?	?
Sea bird nesting sites	yes	yes	no	no	no	yes
Corals (# of species)	180	140	?	?	?	?
Mangrove areas	yes	yes	yes	no	no	no
Sea grass areas	yes	yes	no	yes	no	no
Marine turtle nesting	yes	no	no	no	no	no
Special ecological areas						
Marine park/reserve	yes	1	none	none	none	1
Archeological sites	yes	many	none	none	none	many
Historic/cultural sites	yes	many	yes	yes	none	many
Level of disturbance	N/A	high	high	moderate	high	low
Protected shoreline						
Lagoon (linear feet)	?	?	6,700	0	16,700	0
% of shoreline	?	?	26%	0%	63%	0%
Ocean (linear feet)	?	?	7,600	0	16,500	0
% of shoreline	?	?	26%	0%	63%	0%

STUDY AREA 1

Very little undisturbed terrestrial habitat remains in Area 1 due to the high density of human habitation and the major development activities that continue to take place. There is a small interior mangrove stand in the area.

The ocean shoreline is a beach of gravel, cobbles, and boulders, with some coarse sandy areas and a 7–10 feet (2-3 meters) high gravel berm. Structures are built right at the beach top and only a few properties are protected, usually with a sea wall. The lagoonside shoreline is heavily modified, and the few lagoon beaches are narrow and commonly consist of gravel and coarse sand. Shoreline erosion is common on both shores.

The reefs of this area are highly modified and affected by filling, dredging and quarrying. In addition, water quality is severely degraded due to urban pollution, and there is overfishing.

STUDY AREA 2

The terrestrial habitat in this area is largely coconut plantation. The land mass is relatively large and supports a significant freshwater lens from which water is extracted and trucked to Majuro. Hamlin and Anthony (1987) calculate fresh ground-water storage was 450 to 550 million gallons, with a sustainable yield of 400,000 gallons per day. The potable fresh water has less than 2.6 percent saltwater content.

The oceanside shoreline in this area varies from wide, sandy beaches at the northern and southern ends to a narrow, coral gravel and cobble strip with emerged reef rock at the west point of the islet. The lagoon side of the shoreline is a consistent sandy beach with fine to medium sand. Ongoing erosion is common along the entire oceanside and lagoonside shoreline, but there are no shore-protection structures.

The marine environment in this area is largely undisturbed due to the low population pressure. The oceanside reef varies from mainly sand, rubble and coral to a narrow solid reef flat with little coral cover or sediment and sometimes dense algal cover. The lagoonside reef flat is a sand and rubble flat with sea grass, algae, and sea cucumbers. The large reef hole with coral patches and the outer reef has areas of significant coral cover with some giant clams. There is moderately low reef fish species diversity, but the ocean waters support a high level of fishing.

STUDY AREA 3

The land area here is very narrow and occupied by coconut trees in the less modified western portion. The rest of the area consists of causeways and the airport and runway.

The airport shoreline is a rubble mound revetment on both the lagoon and ocean sides, with some erosion behind the revetment. The causeways in this area are protected by riprap revetment in good condition. Islands connected with causeways are not protected by shore protection structures. Beaches on the ocean side generally consist of gravel and cobble, and the lagoonside beach consists of fine to medium sand, with signs of erosion on both sides.

The ocean and lagoon reefs of this area have a narrow reef flat with no coral cover. A beach rock ramp midway across the present reef flat along the causeways indicates the former presence of islets. The eastern portion of the ocean reef has reef rock quarries with high algal cover, especially coralline algae. The outer lagoon reef has coral cover of 60–80 percent before it drops off into a sand and rubble lagoon slope. The lagoonside reefs support moderate to high reef fish species diversity, and the ocean waters support important pelagic fisheries.

STUDY AREA 4

The terrestrial environment of the numerous small islets in this area consist of coconut trees and strand vegetation.

The oceanside shorelines are generally composed of large coral cobble and plate, with some sand accumulation, especially where there is the reef conglomerate platform. Some limited erosion occurs, especially where the conglomerate platform is narrow or absent. The lagoonside shoreline of the larger islets has sandy beaches, while the smaller islets have cobble and plate beaches, often with conglomerate along the base of the beach.

The marine environment is undisturbed in this area. The oceanside reef is a solid reef flat with no coral or algal growth. The outer limit has a well-developed algal ridge in the wave zone. In between the islets is a scoured reef flat where rapid currents are concentrated between the raised reef conglomerate on either side, particularly on rising tides. The lagoonside of the islets has a narrow reef flat that drops off into a shallow sand and rubble terrace with scattered coral patches and a broad sand slope that descends into the lagoon. Moderately high diversity of reef fish occurs on the lagoon reefs and there is some pelagic fishing, especially for tuna in the ocean and lagoon waters of the area. Many of the islets contain historic and cultural sites.

SOCIOECONOMIC CHARACTERISTICS

DEVELOPMENT FACTORS

Development variables, such as population size and distribution, land-use patterns, and capital investment levels, influence the assessment of socioeconomic impacts of ASLR. These factors are considered with special attention and for the study areas, as available data allow. Data are summarized in Table I7.

POPULATION SIZE AND DISTRIBUTION

The national population numbers 43,380. Roughly two-thirds of the population is concentrated in the two urban centers, Majuro and Ebeye. Growth rates from 1980 to 1988 were exceptionally high by world standards; an annual rate of 4.2 percent in the nation, and at 6.3 percent in Majuro Atoll. In 1988, Majuro, the capital atoll, was home to 19,664 people, or 45.3 percent of the national population (OPS, 1989a).

STUDY AREA 1

Study Area 1 has nearly 15,000 people. This is nearly 80 percent of Majuro's population, the urban section of Majuro, making an exceptionally high population density of 28,724 people/sq. mi., five times the average for Majuro. Houses are built very close together and little land is available for building, gardening, or recreation. Overcrowding is already a serious problem, with schools operating in shifts to accommodate all the students.

TABLE 7. SOCIOECONOMIC CHARACTERISTICS

Types of Data	**Units**	**Marshall Islands**	**Majuro Atoll**	**Study Area 1**	**Study Area 2**	**Study Area 3**	**Study Area 4**
Land area	sq.mi.	70.0	3.75	0.8	1.2	0.4	0.2
Total dry land	acres	44,835	3,402	510	740	230	130
Agriculture	acres	220,000	960	160	450	0	320
Exclusive Economic Zone	sq.mi.	750,000	6.0				
Gross Domestic Product							
Total	US$	68.7m (199.6 m)	54.0m (156.8 m)	40.2m (116.7 m)	4.3m 12.5 m)	7.9m (18.5 m)	52.2th (651.7th)
Growth rate	%/yr	5.9(1.0)	N/A(1.0	N/A	N/A	N/A	N/A4.
Population							
Total	#	43,380 (165,000)	19,664 (73,500)	14,649 (54,300)	1,570 (5,900)	0	19 (160)
Density	#/sq.mi	620 (2,400)	5,240 (19,600)	18.310 (67,900)	1,310 (4,900)	0	95 (800)
Subsistence	#	12,880	1,420	180	1,020	0	19
Growth rate	%/yr	4.2 (3.4)	5.0 (3.4)	N/A	N/A	N/A	N/A
Capital value							
Total	US$	N/A	175m (303b)	158m (2.73b)	17.5m (302.6m)	8.7m (150.6m)	0 1.1m
Growth rate	%/yr	N/A (12.0)	7.5				
Import vs. Export Earnings	ratio	19:1	N/A				
Foreign Aid							
Total annual aid	US$	49.0m (100m)	1.3m				
Aid as % of GDP	%	78 75	N/A				
Land Use							
Agriculture	Acres	23,874	1,100	150	590	50	100
Urban	Acres	600	510	510	0	0	0
Essential Infrastructure							
a. Port/Airport	Acres	135.5	132.5	7.5	125	125	N/A
b. Power station		18	10	10	0.3	0.3	N/A
c. Telecommunications	6.5	7.3	6.3	1.0	1.0	0	
Tourism	Acres	1,024	804	689	0	0	0
Fisheries	Acres	30,000	2,500	490	740	510	470
Industry	Acres	50	30	20	5	0	0
Forestry	Acres	N/A	N/A	N/A	N/A	N/A	N/A
Subsistence Land Use							
Agriculture	Acres	35,548	1,281	N/A	450	0	130
Fisheries	Acres	78,366	2,500	N/A	700	0	450

Types of Data	Units	Marshall Islands	Majuro Atoll	Study Area 1	Study Area 2	Study Area 3	Study Area 4
Production or Capital Value							
Agriculture	US$	8.9m	1.5m				
Urban	US$	2.3m	1.0m				
Essential infrastructure	US$						
a. Port/Airport		27.0m	13.7m	5.0m	0	8.7m	0
b. Power station		85.0m	51.5m	50.m	0	1.5m	0
c. Telecommunications		15.8	12.8m	12.8m	N/A	N/A	N/A
Tourism	US$	3.5m					
Fisheries	US$	6.5m					
Industry	US$	2.0m					
Forestry	US$	N/A					
Subsistence Value							
Agriculture	People/ acre	41	76.8				
Fisheries			93				

Notes: th=thousand m=million b=billion ( )=2022 projections

STUDY AREA 2

Study Area 2, the agricultural center of Majuro encompasses roughly 50 percent more land than Study Area 1, but houses less than 10 percent of the population of Majuro Atoll—i.e. 1,575 people. However, this is still a population density well above the national average, at 1,313 people/sq mi. The availability of arable and buildable land, and the recently enhanced availability of electricity and fresh water, will no doubt enhance migration to the area in the near term.

STUDY AREA 3

Study Area 3 does not support permanent human settlement.

STUDY AREA 4

Study Area 4, a string of sandy cays, supports 19 people—a population density of well below the national average of 95 people/sq. mi.

ECONOMIC FACTORS

Growth of the national economy is restricted by an exceptionally high population growth rate, an inadequate supply of skilled labor, a limited natural resource base, and the geographical isolation of the nation's atolls, from one another and from world markets. Relying heavily on foreign imports, expertise, and aid, the nation is quickly forsaking its subsistence base. Urbanization, fed by a profound disparity between rural and urban income levels, is proceeding rapidly.

Although subsistence agriculture and fisheries still support an average of 50 people per acre, two-thirds of the population now lives in urban areas, where the majority of food consumed is imported (OPS, 1991a). The ratio of imports to exports, 19:1, reflects this growing reliance on foreign goods. A cash economy, fueled by aid transfers, is rapidly displacing the traditional, subsistence-based way of life. Domestic production, consisting primarily of copra, cannot balance imports, resulting in an increasing deficit.

The Marshall Islands EEZ of over 750,000/people sq. mi. contains abundant living and nonliving marine resources, and has one of the world's top three reserves of manganese and cobalt crust (Callies and Johnson, 1989). Efforts to exploit these resources for economic gain are still unrealized.

The gross domestic product (GDP) increased from $31.9 million in 1981 to $68.7 million in 1988 (OPS, 1989a). Although this represents an annual rate of increase of nearly 12 percent, GDP real growth is at approximately 5.9 percent per year. GDP is significantly inflated by foreign aid. In 1991, roughly 78 percent, or nearly $50 million, of current total national revenue is foreign aid, and actual GDP is approximately $25 million, or an actual per capita GDP of between $200 and $500 per year (ADB, 1991). Dominated by a large service sector, the economy is largely sustained by the national government and the U.S. Army Facility at Kwajalein Atoll, which are the sources of at least 40 percent of GDP.

FUTURE ECONOMIC DEVELOPMENT

Future economic development is largely dependent on marine resources. Government subsidies continue to support copra production as a primary economic pursuit on outer islands. The Second Five Year Development Plan (1992-96) includes projects oriented toward mariculture and artisanal fisheries development, sea-bed exploration, and establishment of a long-line fishing fleet. It is hoped that the production of trochus, black-lip pearl oysters, giant clams, and sponges—items worth more per pound than copra—on outer islands will help to make inter-island shipping commercially viable.

The Marshall Islands' vast EEZ may eventually ease the nation's dependence on foreign aid. However, current demographic patterns of rapid population growth may force the nation to direct development efforts to building infrastructure and providing basic services, compromising the nation's potential for self-sufficiency.

LAND-USE PATTERNS

Land is the most valuable resource in the Marshall Islands, as there are less than 70 sq. mi. of land in the entire archipelago, and prime settlement areas are limited.

Ownership parcels (*wetos*) are usually two to five acres in area and run from ocean to lagoon. The *wetos* are held communally by lineage (*bwij*) members, who traditionally cleared and tended the land for subsistence agriculture. Even today, social position is derived according to both present and future land ownership rights, and on most outer islands, a subsistence life style prevails. Approximately 53 people per square mile subsist on agricultural and fisheries activities (OPS, 1991b).

In the Marshall Islands' Constitution, traditional rights of land tenure are unequivocally preserved, and the traditional requirement of consensus decision making, in which all persons with land rights to a certain *weto* must agree on questions of land transfer, is retained.

Agro-forestry has long been a primary component of the nation's agricultural productivity, with copra the primary export for the past 100 years. Coconut groves, many of them planted near the turn of the century, cover 22,000 acres, or 50 percent of the nation's land, although only about half are currently fully productive (OPS, 1991b).

Approximately 1,500 acres of land is covered with stands of other tree crops, including bananas, papayas, breadfruit, and pandanus. An additional 400 acres of land are utilized for the cultivation of root crops and vegetables.

The value of national agricultural production in 1988 was $9 million. Of this, $6 million (67.2 percent), was consumed rather than marketed, and $2.3 million (26 percent), was cultivated in urban areas. The overwhelming majority of urban agricultural production is in Majuro.

The majority of infrastructure investment has been centered in Majuro. Majuro today is the heart of the Marshallese economy, being the most important link to world markets, and the supplier of tertiary education, social, and health services.

PRODUCTIVITY

Since GDP figures were unavailable for the four study areas, estimates were derived by assuming that the proportion of an area's population to that of the entire atoll is equal to that of its GDP. Study Area 3 was treated as a special case, since its productivity is totally derived from the international airport, and since it does not have a population.

STUDY AREA 1

Land in this area is primarily high-intensity urban uses, being the site of the bulk of the nation's industry and services, containing water and power plants, two commercial ports, the majority of government buildings and businesses, and housing for the majority of the nation's commercial work force. Nearly 75 percent of Majuro's population lives in this area. Assuming that 75 percent of the atoll's GDP therefore originates there yields an estimate of $40.2 million for the area's productivity.

STUDY AREA 2

Approximately 80 percent of the land in this area is used for light-intensity nonirrigated agriculture, including the cultivation of coconuts, taro, yams, papayas, breadfruit, and vegetables and the raising of pigs and poultry. The people of Laura obtain a higher price for their copra than the people of outer islands, and an increasing percentage of the residents of Laura work in the D-U-D area. As approximately 8 percent of the population of Majuro lives at Laura, an estimated $4.3 million of the total GDP originates there.

STUDY AREA 3

This area is mainly a long, continuous causeway containing the nation's international airport. An estimate of the productivity of the airport, the nation's only airlink to international markets, is not available. However, estimates of cash flow and profits generated by the airport yield a GDP of $7.92 million for the area. Approximately $43,000 in cash flow per month is generated by the export of live tropical fish, fresh tuna, and giant clams.

STUDY AREA 4

Subsistence agriculture and fisheries are pursued by the area's 19 inhabitants, and some remittances are received. With less than 1 percent of Majuro's population, the estimate of GDP is $52,200. This figure is probably high, given that the people who actually live on the islands lead a subsistence life style.

CAPITAL INVESTMENT LEVELS

The Marshall Islands relies heavily on the United States for funding, provided in the form of annual grants earmarked for capital improvements and development assistance. Direct grants provided under the Compact of Free Association during the period 1986-91 totaled $130.5 million. As scheduled, this amount will decrease to $110.4 during the period 1992-96, and to $95.5 million during 1997-2001. In 2001, funding is scheduled to end, provided that the Compact Agreement is not renewed.

During the period of the First Five-Year Development Plan (1986-90), expenditures for infrastructure development represented 66.3 percent of total project expenditure, or $28.7 million. Most of these funds were directed toward Majuro.

STUDY AREA 1

This area contains the majority of the nation's physical infrastructure, government buildings, businesses and housing, as well as the hospital and community college, saltwater and freshwater public supply lines, and electrical and phone lines. Major existing infrastructure, land, and housing were valued at $158 million.

STUDY AREA 2

This area contains two commercial farms and a number of small piggeries. Major infrastructure, land, and housing were valued at $17.5 million.

STUDY AREA 3

The total international airport was valued at $8.7 million.

STUDY AREA 4

This area contains no significant capital investment.

INSTITUTIONAL ENVIRONMENTAL MANAGEMENT

The importance of environmental management has gained new recognition in the Marshall Islands. A National Environmental Management Strategy has been developed, with oversight from the National Task Force on Environmental Management and Sustainable Development which has high-level representation from all sectors of the government. The strategy represents the first coordinated attempt to integrate sustainable development principles into development plans. In addition, in January 1992 the Ministry of Health Services was renamed the Ministry of Health and Environment.

EXISTING LEGISLATION

Several acts pertaining to various aspects of environmental management are in effect. Acts specifically related to coastal zone and marine resource management include the Coast Conservation Act 1988 and the Marshall Islands Marine Resources Act 1988.

COAST CONSERVATION ACT

Passed in 1988, the Coast Conservation Act mandates the development of a comprehensive coastal zone management plan. The General Manager of the RMIEPA, as the Director of Coast Conservation, is to submit the plan within three years of the Act's passage. However, development of the plan has not yet begun, due to staff shortages and other priorities. Development of a coastal zone management plan was named a top priority during the period 1992-96 in the National Environmental Management Strategy (Crawford, 1991).

MARINE RESOURCES ACT

In 1988, the Marshall Islands Marine Resources Act established the Marshall Islands Marine Resources Authority, which is responsible for the exploitation and conservation of marine resources in the Marshall Islands EEZ.

A reorganization of the Authority, which will take place during 1992 with technical assistance from the Asian Development Bank, is expected to dedicate increased resources to developing a conservation program, including the establishment of a marine resource data base.

EXISTING INSTITUTIONS

Several existing institutions deal with environmental management and planning. The Office of Planning and Statistics is the lead agency for national planning and routinely conducts censuses, socioeconomic studies, and risk assessments that are used to formulate national policy. The Environmental Protection Authority (RMI EPA) is responsible for environmental protection, management and nature conservation. The Marshall Islands Marine Resources Authority establishes responsibility for management and conservation of marine resources. The National Disaster Committee is responsible for planning and coordinating disaster response. The National Weather Station provides meteorological information important to climate change issues. The National Task Force on Environmental Management and Sustainable Development, established in 1991, has oversight responsibility for the development of policies and strategies relating to national environmental management, primarily through implementation of the National Environmental Management Strategy.

IDENTIFICATION OF NONCLIMATE CHANGE DEVELOPMENT FACTORS

Prior to assessing Majuro's vulnerability to future ASLR, it is important to project what the socioeconomic and natural resources may be like in the future. The Common Methodology terms these projections as *scenario variables* and are best estimates based on the current trends and likelihood of activities occurring out to a 30-year period to avoid unnecessary speculation for a 100-year period. ASLR conditions will obviously not be at the 1-meter level as projected out for planning purposes to the year 2100. Given the projected rate of rise for ASLR1 and ASLR2, the global sea level rise estimates are for 8 and 29 cm (this ASLR2 rate approximates the ASLR1 at the year 2100), respectively, so one should not assume a 1-meter rise in 30 years with all its potential consequences. While the scenario variables may be changed to simulate different situations, the following estimates allow for identifying further growth scenarios that would be at risk, given ASLR conditions, in order to begin formulating possible future response strategies.

HUMAN-INDUCED DEVELOPMENTS

Based on recent trends, rapid socioeconomic change can be expected in the near future. The present development scenario was used as the basis for a 30-year projection of population size and distribution, land use and productivity, and capitol investment levels and how such variables would most likely modify the natural resources.

POPULATION SIZE AND DISTRIBUTION

Even though population growth has been significantly high, a gradually diminishing rate of growth was used for a number of reasons to predict future population sizes for Majuro, projecting annual growth at 5.0 percent for the period 1988–90, 4.2 percent for 1991–2000, 3.8 percent for 2001–2010, 3.6 percent for 2011–2020, and 3.4 percent for 2021–22.

Majuro's 1988 population of 19,664, with growth projected as above, results in a population of 73,500, or a density of 19,600 people/sq. mi. in 2022.

Projections show that the population density of Study Area 1 can be expected to reach a critical level (60,000 people/sq. mi.) by the year 2018, when the population reaches 48,000 people. At that time, population increases would have to shift to places like Study Area 2, if they have not already done so.

LAND-USE PATTERNS AND PRODUCTIVITY LEVELS

Land-use patterns and productivity levels would be profoundly affected by the population growth projected above. According to the National Population Policy, an additional 2.2 sq. mi. of land will be required to accommodate the population increase projected for Majuro by the year 2025 (OPS, 1991a). Majuro only has 3.75 sq. mi. Thus, in 30 years, nearly 90 percent of the land area in Majuro will be used for housing This means that less land will be available for agriculture, and that multilevel housing units may become common.

Approximately 130 acres of additional land would be needed to accommodate the population increase in the D-U-D area, if current population patterns and housing customs are maintained (OPS, 1991a). But today, space limitations are already critical in this area. Without widespread landfilling or a shift to high-intensity, multifloor housing units, the area will not be able to accommodate the additional population. This will likely result in increased settlement of other areas on Majuro, including the other three study areas.

If Majuro's GDP continues to grow at 5.9 percent per year (the national average), GDP will reach $380 million in the year 2022. Such growth is unlikely, unless sea-bed mining becomes commercially feasible in the immediate future—which is not likely. It is more likely that the GDP growth rate will taper off as population increases. A growing population will demand more expenditure for essential infrastructure and services, diminishing funds available to invest in the economy. The scenario presented in Table 8 was used to project the GDP into the year 2022.

TABLE 8. PROJECTED GROWTH OF GDP, 1988–2022

Period (Years)	Rate of Increase (%/year)
1988–90	5.9
1991–95	5.0
1996–00	4.0
2001–05	3.0
2006–10	2.5
2011–15	2.0
2016–20	1.5
2021–22	1.0

Changed productivity will be linked to changes in land use in some areas. Study Area 2 is the largest area of relatively lightly populated land on Majuro and has water and electricity. The population will likely surpass projections, and at least half of its land area will be used for housing, which will diminish agricultural productivity, but may increase service and industrial productivity.

As the Marshall Islands continue to grow, the role of the international airport in Study Area 3 will increase, resulting in an increase in productivity. The small islets in Study Area 4 are unlikely to become major population or industrial centers by the year 2022. However, they are very similar to other islets that have been targeted as sites for development of small-scale tourist resorts and an increase in productivity is projected based on this.

CAPITAL INVESTMENT LEVELS

The projected increase in population will greatly raise capital investment levels, as increased demand for government services will necessitate an expansion of infrastructure. Also, increased demand for fresh water will necessitate the construction of a desalinization plant or a greatly expanded community water catchment surface, as the present system of collection, storage, and distribution is already insufficient, and water is frequently rationed.

Capacity for electricity generation will need to be increased from 38,000 to 114,000 MW/hr. by the year 2025 (OPS, 1991a). Schools and hospital facilities, expanded sewerage facilities and communications systems will also be required to meet the needs of the population.

During the next 30 years, it can be anticipated that the shoreline devoted to port facilities will increase for commercial purposes, as well as a marina and boat dock. In all cases, if these facilities are not built properly, to include ASLR and increased flooding potential, these facilities will be at high risk.

The capital value of physical infrastructure will increase by 7.5 percent a year on Majuro from 1988-2000. Projecting that this rate increases to 10 percent during the period 2001-2010, and 12 percent during 2011–2022, the capital value of Majuro is expected to grow to $3.03 billion by 2022, as in Table 9.

TABLE 9. PROJECTED GROWTH IN CAPITAL VALUE, 1988–2022

Period (Years)	Rate of Increase (%/year)
1988–2000	7.5
2001–2010	10.0
2111–2022	12.0

NATURAL DEVELOPMENTS

The growth of the Marshall Islands population and economy during the 30-year development scenario period will have effects on the natural systems of Majuro. These include degradation of terrestrial and marine habitats, of the flora and fauna that those habitats support, and of water quality in general. In addition, natural processes will continue, notably shoreline erosion and accretion.

The most likely effects will be the loss of agricultural land in Study Area 2 by half due to urbanization, loss of vegetation that serves to buffer winds and waves, loss of coral reef for building materials, overfishing by sport and subsistence fisherman in the lagoon area, and decreased water quality in the lagoon. The more affluent new homeowners are expected to be located near the water, and structural works to protect against erosion will be built near the waters' edge. This is likely to erode the sandy beaches in those areas. More than a doubling of the population will mean road improvements (wider, etc.), taking more space and clearing vegetation. Many of the roads now have berms along the side to protect from small overwash problems. These, too, will reduce vegetative cover.

Loss of land through shoreline erosion by natural processes that are often exacerbated by human activities, is already a major concern on Majuro. The importance of land will increase with the population and economic growth predicted for 2022. Shoreline protection and landfill activities will continue and will probably expand greatly under a normal development scenario, in order to both protect and create valuable land.

The health of the coral reefs is particularly important in considering future scenarios. Flooding can occur from both the oceanside and lagoonside. It is assumed that coral reefs can keep up with sea level rise and this would help to diminish the impacts of at least smaller storm waves, as well as provide new sediment materials for beaches. However, the shallow coral reefs will continue to be affected by economic development and population growth on Majuro, unless major environmental management efforts are made. Significant portions of the lagoon reef flat will be reclaimed to create land or used for building materials. The urban areas, which will be larger, more dense, and spread into new areas, will continue to degrade reefs with solid and liquid wastes. Water quality will thus continue be degraded, with effects on coral reef and other inshore organisms.

While these impacts may be localized, they often will occur where the vulnerability factor is the greatest—near the population centers themselves. If human activities disrupt coral growth, then vulnerability will not be reduced by natural factors, and more costly protective works would be needed to reduce the vulnerability. Figures 8 and 9 illustrate the erosion/accretion process occurring in Study Area 1. Coral has been mined on the lagoon side, and erosion is occurring on both sides and is critically close to the main highway, and overwash from storms is a problem. The figures also illustrate accretion occurring on both sides of the erosion zone.

FIGURE 8. COASTAL RESOURCE ATLAS SHOWING CRITICAL EROSION AREAS

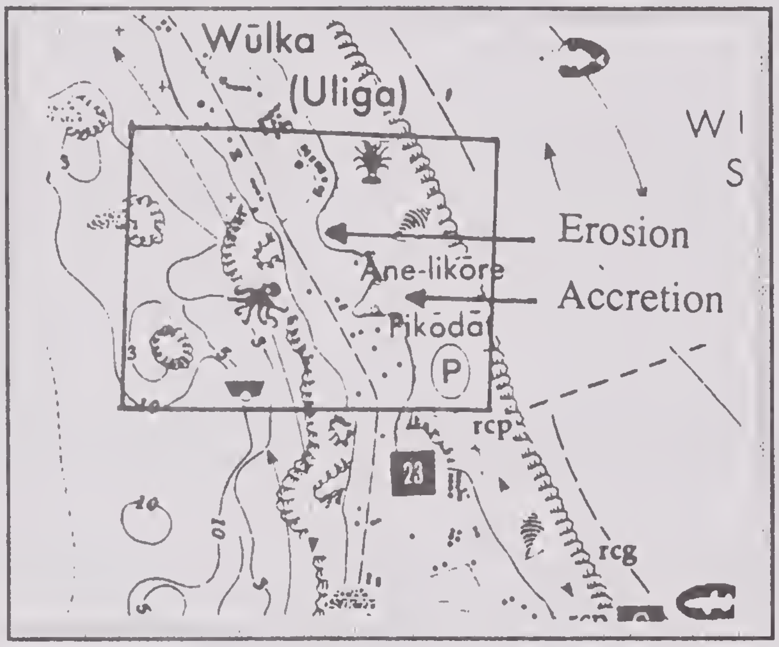
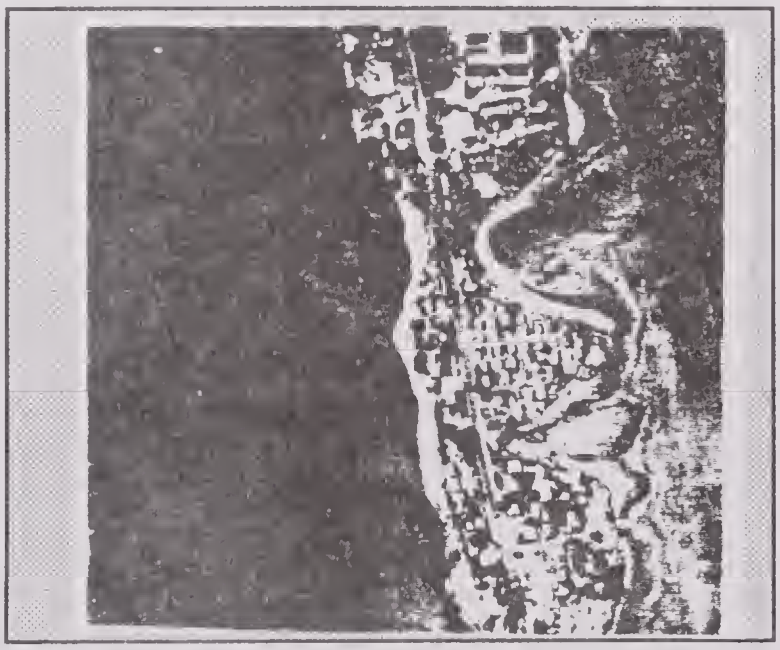


FIGURE 9. AERIAL VIEW OF ENCLOSED AREA SHOWN IN FIGURE 8



At the same time, it is assumed that significant strides will be made to protect water quality in the future, and that continued environmental degradation based on population growth can be properly managed. Nonetheless, population growth in such a closed environment will have adverse effects.

PHYSICAL CHANGES AND NATURAL SYSTEM RESPONSES

This step in the assessment of vulnerability attempts to quantify the physical changes and natural system response to ASLR. It is followed by a socioeconomic impact assessment of related damages, including direct losses and increased risk of flooding.

PHYSICAL CHANGES

SHORELINE EROSION

The Bruun Rule (Bruun, 1988) was used to estimate shoreline erosion at Majuro. Shoreline retreat as the direct result of sea level rise is estimated using a generalized shoreline slope of 1/10 on both the ocean side and lagoon side. The additional shoreline retreat would thus be 10 feet (3 m) and 33 feet (10 meters) for ASLR1 and ASLR2, respectively. Table 10 presents estimated total shoreline retreat due to ASLR1 and ASLR2, and Table 11 shows how much dry land is lost based on the shoreline retreat.

TABLE 10. ESTIMATES OF SHORELINE RETREAT DUE TO SEA LEVEL RISE

Location	**Shore Elevation** *(feet)*	**Water Depth** *(feet)*	**Sediment Deposit** *Width (feet)*	**Shoreline Retreat**	
				ASLR=1	*ASLR=2*
Study Area 1					
Ocean					
Jaroj-Wulka	8	2	700	80	60
Telap	8	2	300	40	130
Lagoon					
Jaroj-Wulka	6	28	750	30	110
Telap	6	28	400	20	70
Study Area 2					
Ocean					
N-Section	10	2	1,400	130	420
S-Section	10	2	500	50	170
Lagoon					
N-Section	6	28	370	20	70
S-Section	6	28	1,250	50	150
Study Area 3					
Ocean	8	2	350	50	150
Lagoon	6	14	400	30	100
Study Area 4					
Ocean	8	2	700	80	50
Lagoon	6	14	430	40	130

TABLE 11. ESTIMATES OF DRY LAND LOST DUE TO SEA LEVEL RISE AND EROSION

Location	**Unprotected Shoreline** *(feet)*	**Present Dryland** *(acres)*	**Dry Land Lost**	
			ASLR=1 (acres)	*ASLR=3.3* (acres)
Study Area 1	44,000	510	50	160
Ocean	22,000	35	110	
Lagoon	22,000	15	50	
Study Area 2	28,000	740	45	140
Ocean	16,000	35	110	
Lagoon	12,000		10	30
Study Area 3	16,000	230	15	50
Ocean	8,000	10	30	
Lagoon	8,000	5	20	
Study Area 4	22,000	130	30	100
Ocean	11,000		0	75
Lagoon	11,000		10	25

The shoreline retreat with an ASLR of 1 foot is 40–130 feet on the ocean side of the study areas, and from 20–50 feet on the lagoon side. The corresponding dry land loss is 15 acres in Study Area 3 and as much as 50 acres in Study Area 1. With an ASLR of 3.3 feet, the shoreline retreat ranges from 130 to 420 feet on the ocean side and from 70 to 150 feet on the lagoon side. The dry land loss ranges from 50 acres in Study Area 3 to 160 acres in Study Area 1.

These estimates are approximate, and are based on very generalized conditions. In reality, there are many variables, and prediction of the response to sea level rise becomes much more difficult. Much site-specific research is needed to determine the extent of beach erosion that currently exists and will result from ASLR.

FLOODING

Flooding by wave runup and overtopping is a constant threat in the Marshall Islands due to the low elevation of land areas. Even in the absence of ASLR, significant wave activity is generated by tropical cyclones, major storms and strong winds. Wave runup which overtops beach berms or protective structures and floods substantial land areas is not uncommon as a result of these events. When ASLR is added to the calculations, major inundation and flooding are predicted.

Tables 12 and 13 present wave run-up elevation and distance inland for the ocean side and lagoon side of the study areas. These have been computed by adding significant wave runup to still-water rise. When a substantial inundation distance is calculated or the still-water level exceeds the beach crest, flooding is predicted (indicated by a code FL in the tables). The table shows that in many cases the significant wave run-up nearly reaches the beach crest even during an annual event with no ASLR.

TABLE 12. OCEANSIDE INUNDATION LIMITS
(IN FEET IN REFERENCE TO MSL)

	Wave Runup (Elev/Dist)		
Location	*Annual Extreme*	*50-Year Extreme*	*Typhoon Event*
ASLR = 0 feet			
Study Area 1			
Jaroj-Wulka	7/80	9/90(FL)	FL(10.5/100)
Telap	7/80	9/90(FL)	FL
Fuel Tanks	FL(13/380)	FL(13/500)	FL(13/550)
Study Area 2			
N-Section	6/40	8/50	11/100(FL)
S-Section	7/60	9/90	FL(11/230)
Study Area 3			
Causeways	6/170	8/180(FL)	FL
Islands	7/60	9.5/70	FL
Runway section	8/17	FL(9.5/26)	FL
Study Area 4	N/A	N/A	N/A
ASLR = 1.0 feet			
Study Area 1			
Jaroj-Wulka	8/90	9.5/100(FL)	FL
Telap	8/90	FL	FL
Fuel Tanks	FL(13/400)	FL(13/540)	FL(13/560)
Study Area 2			
N-Section	7.5/50	9.5/60	FL
S-Section	8/80	9.5/130	FL
Study Area 3			
Causeways	7/175	FL(9/210)	FL
Islands	8.5/70	10/100(FL)	FL
Runway section	FL(9/22)	FL(10/33)	FL
Study Area 4	N/A	N/A	N/A
ASLR = 3.3 feet			
Study Area 1			
Jaroj-Wulka	FL(11/100)	FL	FL
Telap	FL	FL	FL
Telap Fuel Tanks	FL(13/560)	FL(13/570)	FL
Study Area 2			
N-Section	11/70(FL)	FL(11/180)	FL
S-Section	10/200(FL)	FL	FL
Study Area 3			
Causeways	FL	FL	FL
Islands	FL(10/200)	FL	FL
Runway section	FL	FL	FL
Study Area 4	N/A	N/A	N/A

TABLE 13. LAGOON-SIDE INUNDATION LIMITS IN FEET IN REFERENCE TO MSL

	Wave Runup (Elev/Dist)		
Location	**Annual Extreme**	**50-Year Extreme**	**Typhoon Event**
ASLR = 0 feet			
Study Area 1			
JaroJ-Wulka	5/80	5.5/100	FL
Telap	5/80	5.5/140	FL
Telap Dock	8.5/0	9/20	FL(10/220)
Study Area 2			
N-Section	5/50	5.5/70	FL
S-Section	4.5/55	5/65	FL
Study Area 3			
Causeways	5/7	5/8	FL(9.5/20)
Islands	4.5/35	5/40	9/70
Study Area 4	N/A	N/A	N/A
ASLR = 1.0 feet			
Study Area 1			
Jaroj-Wulka	6/130	6/240(FL)	FL
Telap	5.5/190	6/290(FL)	FL
Telap Dock	9/30	9/50	FL(11/300)
Study Area 2			
N-Section	5.5/130	FL(5.5/350)	FL
S-Section	5.5/80	6/100	FL
Study Area 3			
Causeways	6/9	7.5/11	FL(10/24)
Islands	6/45	6.5/50	9.5/90
Study Area 4	N/A	N/A	N/A
ASLR = 3.3 feet			
Study Area 1			
Jaroj-Wulka	FL(7.0/630)	FL(7.5/700)	FL
Telap	FL	FL	FL
Telap Dock	FL(9.5/110)	FL(9.5/150)	FL
Study Area 2			
N-Section	FL	FL	FL
S-Section	8/170(FL)	8.5/190(FL)	FL
Study Area 3			
Causeways	FL(9/20)	FL(9.5/21)	FL
Islands	8.5/65	9/75	FL
Study Area 4	N/A	N/A	N/A

Note: FL = Flooding; (FL) = Flooding in Partial Sections.
N/A = Not Available.

These estimates should be considered conservative because even if the significant wave run-up does not reach the top of the shoreline, the occasional, larger wave run-up elevations could be expected to overtop the beach crest, even during annual events. However, the calculated wave run-up elevation assumes the natural topography of the shoreline and ignores the effects of building and other man-made structures. Where these occur, they would decrease the actual run-up due to the blocking effect of the buildings.

It was not possible to map inundation areas due to the lack of detailed topographic maps. Topographic maps with 1-foot contours are available for the D-U-D area (Study Area 1). However, inundation mapping of ASLR1 and ASLR2 was only possible on large scale maps. When reduced to page size, inundation lines were not distinguishable. However, estimates of flooding were calculated. Table 14 shows the area that is expected to be flooded as a result of runup and overtopping during normal annual events and annual events combined with ASLR. Note that significant flooding is predicted by adding ASLR 2 to normal yearly runup events.

TABLE 14. FLOODING AREA ESTIMATES FOR ANNUAL EVENT CONDITIONS (IN ACRES)

Area	**Total Land (acres)**	**ASLR = 0**	**ASLR = 1**	**ASLR=3.3 (FT)**
Study Area 1	510			
Ocean		60	65	255
Lagoon		50	90	255
Study Area 2	2 740			
Ocean		20	25	50
Lagoon		15	30	50
Study Area 3	230			
Ocean		10	65	115
Lagoon		10	10	115
Study Area 4	130	N/A	N/A	N/A

Note: N/A = not available.

FLOODING FREQUENCY

In the flooding frequency estimates, flooding occurs if the wave run-up exceeds the typical "critical" beach crest elevation in the study areas. Tables 15 and 16 show the flooding frequency estimates on the ocean side and the lagoon side.

TABLE 15. PREDICTED OCEANSIDE FLOODING FREQUENCY

Study Area	**Critical Beach-Crest Elevation (feet)**	**Flooding Frequency (times/yr)**		
		ASLR=0	*ASLR=1*	*ASLR=2*
Area 1	7.5	1/30	1/5	>10/1
Area 2	11	<1/100	<1/100	1/1
Area 3	8	1/5	10/1	>10/1
Area 4	N/A	N/A	N/A	N/A

TABLE 16. PREDICTED LAGOON-SIDE FLOODING FREQUENCY

Study Area	Critical Beach-Crest Elevation (feet)	Flooding Frequency (times/yr.)		
		ASLR=0	*ASLR=1*	*ASLR=2*
Area 1	5.5	1/60	1/10	>1/1
Area 2	5.5	1/60	1/5	5/1
Area 3	7.5	<1/100	<1/100	>10/1
Area 4	N/A	N/A	N/A	N/A

These tables highlight the dramatic increase in flooding frequency that can occur with sea level rise. For example, a predicted oceanside flood frequency increases from one time in 30 years at present to more than 10 times per year with a 1.0-meter rise in sea level.

WATER RESOURCES

ASLR may affect the loss of ground water resources in two ways. One is increased frequency of flooding due to storm high tides. Storm flood damage is not necessarily permanent, but it may make the ground water unusable at a critical time. The second threat is from island area loss, either by frequent tidal inundation of low-lying areas or by erosion of shoreline.

Miller and Mackenzie (1988) estimated a loss of ground water in Laura (Study Area 2) due to island area loss. Beginning with an initial island width of 1,130 meters, loss of 150 meters from each shore was estimated as a response to an ASLR of 1 meter by the Bruun rule. The original ground-water lens cross-section area is 14,000 m^2. After a 1-meter sea level rise, the lens area would be 7,660 m^2—a 45 percent reduction of the lens cross-section area. For the study model, they used a lens boundary representing 50 percent saltwater content.

These procedures can be used to calculate reduction of the ground water lens caused by the reduction in land area presented in Table 11. The results are presented in Table 17. A substantial reduction in the size of Majuro's only major ground-water supply is predicted by these simple calculations, especially under ASLR2. This represents a serious loss of an essential resource on an island where water shortages and rationing are not uncommon.

TABLE 17. PROJECTED REDUCTION OF THE FRESHWATER LENS IN STUDY AREA 2

ASLR *(feet)*	Shoreline Retreat *(feet)*	Island Width *(feet)*	Lens Height *(feet)*	Lens Depth *(feet)*	Lens Area *(ft^2)*
0	0	3,700	2	81	150,000
1	200	3,500	1.9	77	135,000
3.3	600	3,100	1.7	69	105,000

RESPONSES OF NATURAL SYSTEMS

It is impossible to precisely assess the response of natural systems to ASLR physical changes for Majuro or the study areas. The major effect on natural systems that the predicted physical changes would have would be the loss of land. Land itself is an invaluable resource in the Marshall Islands, and particularly on Majuro. Otherwise, no unique or special habitats or rare and endangered plants and animal species would be lost by the reduction in land area. Overtopping and flooding would similarly have major general impacts on terrestrial vegetation and habitats, but none of this is unique to Majuro.

ASLR will most likely proceed with chronic erosion and minor inundation events, punctuated with major flooding and land loss during extreme events. Shoreline vegetation will be lost to chronic erosion and limited inundation, as is the present case. Extreme events may result in long-term changes through extensive land loss and die-off of inundated vegetation. Salinization of the groundwater lens could result in the loss of existing vegetation, especially along the fringes.

It is assumed that shallow nearshore marine communities will not be significantly affected by ASLR. Coral reefs in particular have a geologic record of adaptation to changes in sea level. The coral reefs of Majuro support habitats, plants or animals that are common to the whole country and probably the Central Pacific. It is important to note that ASLR may be accompanied by other oceanographic changes that make coral reef response unsure. In addition, coral reefs are now subject to human impacts, particularly reduced water quality, which may reduce their ability to respond to ASLR.

IDENTIFICATION AND SPECIFICATION OF RESPONSE STRATEGIES

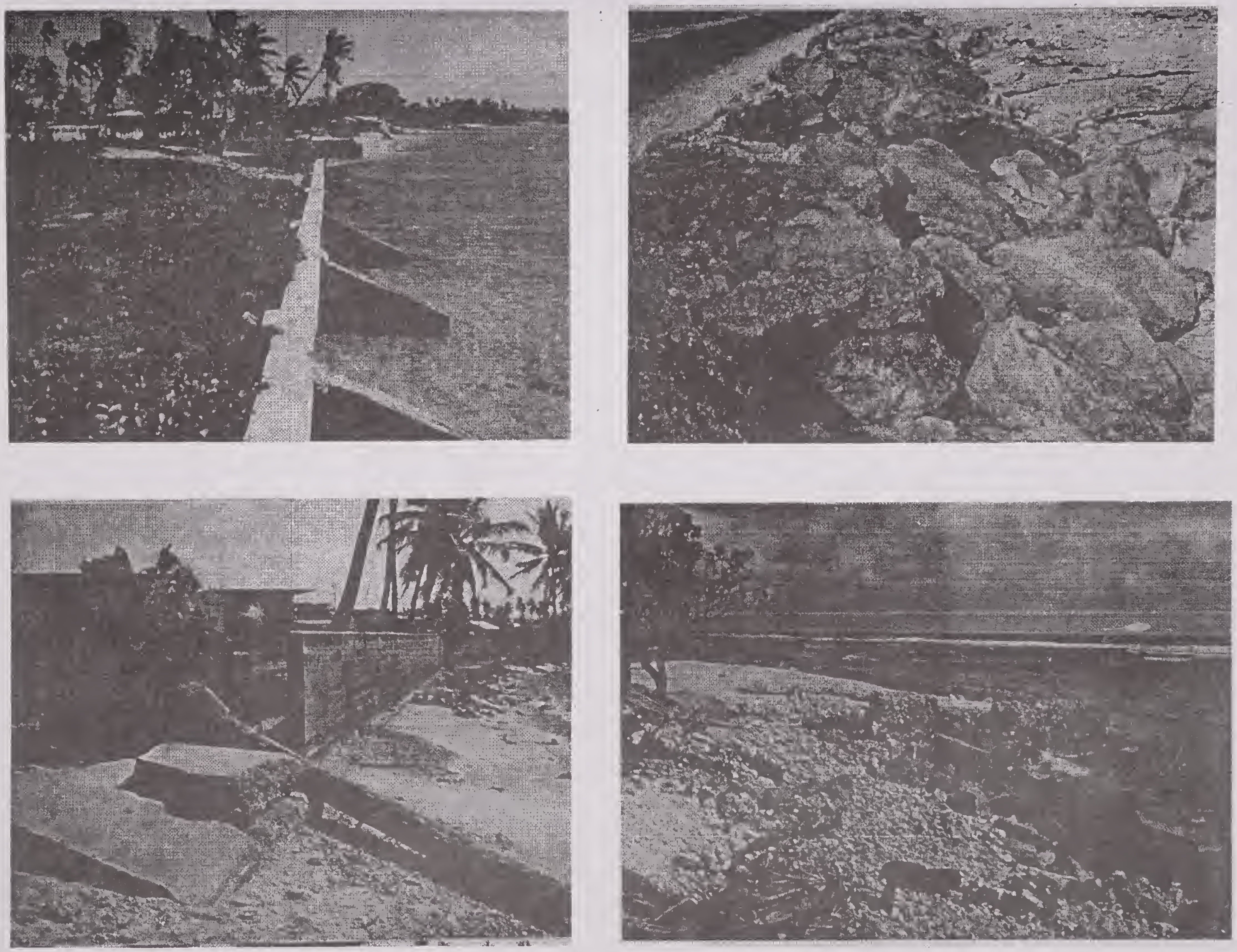
Potential response options to ASLR, as identified by the IPCC, include protection, accommodation, retreat and no response (the present situation for baseline analysis). No single option fully satisfies a country's needs (i.e., there will be a combination of responses over time and spatially). The technical and scientific aspects of each of these were examined in the general context of an atoll island. Second, more specific examples of applying response strategies to the study areas on Majuro were developed. In the end, response strategies must be decided by the Marshall Islands by identifying risks, establishing priorities, evaluating in-country goals and capabilities, and obtaining support from outside sources.

PROTECTION STRATEGY

Atoll islets are primarily composed of unconsolidated coralline material, and their shorelines require stabilization and protection against erosion by wave action, which is expected to increase with ASLR. When wave run-up exceeds the crest elevation of the foreshore land and ground elevation is lower than the wave run-up height, wave overtopping and flooding of the backshore area occur.

Protection against flooding damage by overtopping waves can be accomplished by: (1) improving the wave-energy dissipating characteristics of the shoreline, (2) constructing adequate shore protection with a crest elevation above wave run-up height, (3) constructing a wall or berm above the existing shoreline or shore protection crest to prevent overtopping during infrequent but severe storm wave attack, and/or (4) providing a scour-resistant surface behind the shoreline crest and grading the backshore for proper drainage during overtopping conditions.

FIGURE 10. TYPICAL PROTECTIVE STRUCTURES ON MAJURO ATOLL



These photographs show examples of sea walls (left), a revetment made of large "armor" stone (upper right), and a gabion sea wall made of coral rubble packed in wire.

SHORELINE-PROTECTION STRUCTURES

Revetments, sea walls and bulkheads are commonly used shore-protection structures placed parallel to the shoreline to separate the land area from the water. They protect only the land immediately behind them. When they are built on a receding shoreline, the recession will continue and may be accelerated on adjacent shorelines. In addition, structures reflect wave energy that may cause erosion seaward of the structure. Vertical, smooth walls result in greater wave energy reflection and more scour. Coarse rubble slopes more effectively dissipate and absorb wave energy, reducing wave runup, overtopping and scour.

A revetment is a facing of erosion-resistant material that protects a shoreline from direct erosion by waves. The most common method of revetment constructions an armor layer of stone or concrete units over an underlayer and bedding layer. The armor stones are sized according to the design wave. The underlayer and bedding layer distribute the weight of the armor layer and prevent loss of shoreline material through voids in the revetment.

Sea walls protect the land from wave damage and are a long-lasting, low-maintenance shore protection method requiring limited shoreline space. The near vertical seaward face of sea walls deflects wave energy and can cause severe erosion and scour at the base of the wall. Undermining is one of the most common causes of sea wall failure, and failure of one section can often initiate the failure of the entire wall. Because they dissipate little wave energy, smooth, vertical sea walls are more easily overtopped by waves than sloping, irregular walls.

A bulkhead is a vertical wall constructed of sheet piles driven into the ground and stabilized by tie backs. The primary purpose of a bulkhead is to retain landfill in sheltered waters. The smooth vertical face does not absorb wave energy and is easily overtopped. Bulkheads are not appropriate for shore protection, and should be limited to use as retaining structures in harbors.

SHORELINE-PROTECTION DESIGN

Revetment and sea wall heights are designed to prevent significant wave overtopping, despite the water level rise and severity of wave attack. In some cases, however, it is not feasible and economically justifiable to construct a non-overtopping structure.

It is important to ensure that the foundation of any shore-protection structure is adequate to protect against failure due to scour and undermining by wave action, particularly for sea walls. Ideally the shore protection should be constructed on solid, nonerodible substrata.

Shore-protection designs for atolls are dependent on the availability of construction material. The first choice for revetment material is limestone, quarried directly out of the reef flat. Revetments can also be constructed with cast-concrete armor units. Coral aggregate and sand for use in the concrete mix are readily available and can be obtained directly from the lagoon or old quarry sites. Unconsolidated sand and earth berms are effective against overtopping, but they are extremely vulnerable to erosion and scour during periods of high wave runup.

COASTAL FLOOD PROTECTION

During overtopping situations, damage to the backshore immediately behind a shore-protection structure can be reduced or eliminated by constructing a scour-resistant surface of concrete, asphalt, or stone. Coupled with a drainage system the scour protection can prevent the damage that could lead to significant damage to the structure itself. The drainage control is also an effective means for reducing damage and flooding of the backshore area during overtopping conditions. Properly graded slopes and drainage channels can reduce the inundation limits and hasten the dewatering of flooded areas.

BERM ELEVATION

Augmentation of natural beach berms may provide a short-term possibility for shore protection. Material similar to that which makes up the atoll berms is available from the reef and lagoon. However, this material will be as erodible as the natural berms and will require constant replenishment from limited local sources.

ACCOMMODATION

The lack of naturally occurring high ground on low-elevation islands reorients the use of accommodation as a strategy. Raising existing structures on pilings, and planning new structures with raised first levels, would accommodate occasional flooding and help to minimize property damage during storms. Overall, though, it would be desirable to raise the general ground elevation of the atoll above the possible future still-water level.

Land infilling would best be carried out with construction of shoreline protection at the same time and location. Lagoon-side reefs could be filled prior to protection, creating land that could be made available to migrants from other areas affected by ASLR. The availability of suitable landfill material would likely be a constraint to large-scale land raising. Local reef and lagoon materials are appropriate; however, the amounts available would be limited. Imported landfill material would be much more expensive. Strategically, the Marshall Islands may need to consider using all or portions of islets as sources of fill material if it is determined that they would not be defended and lost to erosion.

Accommodation strategies could also include adaptive economic activities for flooded areas, such as aquaculture or the culturing of halophytes. A heavier reliance on mariculture as a source of revenue is a possible means to offset economic losses associated with inundated coastal properties. The future may also hold the possibilities of "floating cities"— platforms for habitation, anchored in the lagoon as a means of providing safe havens, tourism, etc. While this is mere speculation, the point is to consider that the future may hold viable accommodation alternatives that are now only being thought about.

RETREAT

Even on low-elevation islands, different areas have different vulnerablilty to ASLR based on a number of factors, mainly geomorphologic. Areas that are less vulnerable, if identified, are areas to which retreat is possible. It is necessary to develop the means to identify which islands, or even which islets within an atoll, are more or less vulnerable to wave overtopping and flooding. With the identification of relative vulnerability, planned and precautionary retreat to less vulnerable areas is possible as a part of development planning and disaster response.

Retreat to naturally occurring higher ground is not possible on a low island, since there is no natural high ground of significant elevation. However, higher-elevation areas could be created through a combination of installing shore protection and raising of land elevation—i.e., a combination of protection and accommodation strategies. These artificial high grounds should be created in areas that have been identified as naturally less vulnerable. Such areas could provide core zones among and within islands for retreat under extreme conditions, especially when coordinated with infrastructure development and disaster response planning.

Based on the tables of physical impacts in this paper (Tables 10–17), it is clear that the oceanside of Study Area 2 provides the greatest amount of safety from erosion and flooding. Prior to 1900, the majority of the Marshallese population lived on Laura and safety would certainly have been one of the factors. This factor should be considered in any future plans for Study Area 2 to include emergency evacuation shelters, etc. Of course, these plans would have to be coupled with adequate warning of major storms or inundation events.

In extreme conditions, and in the absence of creating higher ground that is habitable under extreme conditions, the only option may be to retreat completely. Abandonment—i.e., a population relocating to another island—is not unknown in the South Pacific. Atoll populations have historically moved to other atolls or to high islands as a result of drought, cyclone, tsunami or subsidence that have rendered the low-elevation island uninhabitable. Complete retreat from a country of low-elevation islands to a foreign country requires addressing important issues, such as the loss of the Marshallese culture and life style, which are closely associated with the land and the ocean, and the loss of sovereignty. Abandonment should be a last choice, but one based on the safety of the citizens of the Marshall Islands.

NO RESPONSE STRATEGY

Overtopping of shorelines and shore structures by waves leading to frequent flooding is already a severe threat to existing social, economic, and political institutions. Passive coastal management—i.e., avoiding development in areas vulnerable to inundation—would be ineffective as the threat of flooding is similar for all areas with the nearly uniform low elevation.

A no response strategy would be a continuation of the ad hoc and crisis response measures normally used to address erosion and flooding problems in more valuable or densely populated areas. For outer islands and islets with low populations, no action in response to the threat of wave overtopping and flooding would generally be a continuation of the status quo due to the lack of resources for coastal management, disaster response planning, and capital outlay for facilities.

SPECIFICATION OF RESPONSES

PROTECTION

Protection Conditions for Majuro

The annual wave event for ASLR1 and ASLR2 and the 50-year and typhoon-event waves for ASLR1 were used to determine shore-protection needs for Majuro. ASLR2, when combined with the 50-year and typhoon wave conditions, results in a water level exceeding most of the land elevation of Majuro. Specifics of protecting Majuro from such excessive water level rise were not calculated. The design wave heights calculated for the study areas are shown in Table 18. A major difference in wave height is shown for different portions of the ocean side in the study areas, demonstrating how difficult it is to make design and cost projections with the limited amount of information that is available.

TABLE 18. DESIGN WAVE HEIGHTS AT SHORE (IN FEET)

Study Area	**Annual Wave Event**			**ASLR1 w/ Storms**	
	No ASLR	*ASLR1*	*ASLR2*	*50-year*	*Typhoon*
Study Area 1					
Ocean	3	3	5	4	6
Fuel Tank Area (Ocean)	17	17	19	18	20
Lagoon	3	4	6	5	7
Study Area 2					
Ocean	3	3	5	4	6
Lagoon	2	2	4	3	5
Study Area 3					
Ocean	3	4	5	5	6
Lagoon	2	2	3	3	5
Study Area 4					
Ocean	2	3	4	3	5
Lagoon	2	2	3	3	5

Table 19 gives generalized revetment elevations based on calculated wave runup using the design wave heights in Table 18. The structure crest elevations may allow some wave overtopping, but are high enough to prevent wave overtopping from resulting in significant inland flooding. The table shows that storm conditions coupled with ASLR1 require structure heights similar to those required for ASLR2 under annual conditions.

TABLE 19. GENERALIZED REVETMENT CREST ELEVATIONS VERSUS ASLR AND WAVE CONDITIONS (FT ABOVE MSL)

ANNUAL EVENT

	No ASLR			ASLR1			ASLR2		
	BK	*RP*	*ST*	*BK*	*RP*	*ST*	*BK*	*RP*	*ST*
Ocean	9	8	–	10	9	9	–	13	12
Fuel Tanks (Ocean)	–	–	15	–	–	16	–	–	20
Lagoon	8	7	–	9	9	–	–	13	12

ASLR1

Storm Conditions

	50-year			Typhoon		
	BK	*RP*	*ST*	*BK*	*RP*	*ST*
Ocean	–	11	10	–	–	14
Telap Fuel Tanks (Ocean)	–	–	18	–	–	22
Lagoon	–	10	9	–	–	14

Notes:
– = Not applicable.
BK = Concrete block, rubble or cube revetment.
RP = Graded riprap revetment.
ST = Quarrystone or concrete tribar or cube armor revetment.

Protection Costs for Majuro

Shore-protection costs for Majuro are based on design conditions for Kwajelein Atoll, where a major study on shore protection was undertaken (Sea Engineering, Inc., and R. M. Towhill Corp., 1988) as the conditions for Majuro are similar. Based on the above information, Table 20 gives the shore-protection cost estimates for Majuro per 100 feet shoreline. Study Areas 1, 2, and 3 are considered to have on-site construction and maintenance capabilities. Study Area 4 is categorized to be outer islands. The cost estimates include both construction costs and 25-year life cycle maintenance costs. However, protection against higher sea level does not always result in greater costs, as shown in the table.

There is considerable increase in cost when on-site capabilities are not possible. The choice and availability of materials also greatly alter cost estimates, with riprap and armor stone the least expensive. Riprap revetments, while cost-effective, may not be sufficiently large to withstand the extreme design waves because of the size of the rocks that could be quarried from Majuro reefs. Thus, security of those areas protected with riprap may not be assured, and maintenance costs would be quite high, as major storms would be likely to damage sections.

With sufficient financial resources and construction materials, shore protection of any part of Majuro is feasible under the ASLR conditions examined in Table 20. Applying this information to examples in the study areas allows more detailed technical and cost evaluations to be made.

Protection of Specific Areas

In the short term full protection will likely be considered as appropriate initially for Study Areas 1 and 3. Therefore, this is further developed here as a realistic example of protection costs. In Study Area 1, the entire shoreline would be protected, and in Study Area 3, at least the entire airport would be protected.

Table 21 gives cost estimates for shore protection for the entire shoreline in Study Area 1 and for the airport in Study Area 3. The table gives shore protection cost estimates for three cases: (1) ASLR1 and the typhoon wave, (2) ASLR1 and the 50-year wave, and (3) ASLR2 and the annual wave. The shore-protection costs given in Table 21 are for shore protection structures only; they do not include the cost of landfill material to elevate the study area.

ACCOMMODATION

As with protection, accommodation is possible for any of the study areas with sufficient financial resources, technical expertise, technology and materials. The application of accommodation strategies would probably commence with the raising of structures on stilts or pilings. This would most likely be applied initially in those areas with large numbers of important buildings at risk, notably ocean shoreline buildings in Study Area 1. A detailed analysis of the technical and financial aspects of raising buildings was not possible as part of this study.

The raising of land elevation by putting in fill material could be considered as a possible response for any of the study areas. Realistically, as with protection, it would initially be applied to areas of high value and high population density. Detailed study of relative vulnerability is required in order to target land raising to those areas least susceptible already to overtopping and inundation.

TABLE 20. MAJURO SHORE-PROTECTION COST ESTIMATES PER 100 FEET FOR 25-YEAR LIFE CYCLE (THOUSANDS OF U.S. $)

Shore Protection Type	**Annual Event**			**ASLR1 w/ Storms**	
	No ASLR	*ASLR1*	*ASLR2*	*50-year*	*Typhoon*
			STUDY AREAS 1, 2, & 3		
Ocean Side					
Riprap	$60	$79	$10	$94	–
Concrete Block	356	–	–	–	–
Concrete Rubble	278	–	–	–	–
Armor Stone	–	74	140	83	146
Concrete Cubes	–	302	317	262	290
Tribar	–	–	148	–	171
Lagoon Side					
Riprap	54	79	110	87	–
Concrete Block	320	–	–	–	–
Concrete Rubble	250	–	–	–	—
Armor Stone	–	68	140	75	146
Concrete Cubes	–	264	262	264	302
Tribar	–	–	148	–	171
			STUDY AREA 4		
Ocean Side					
Riprap	$341	$356	$499	$427	–
Concrete Block	637	–	–	–	–
Concrete Rubble	685	–	–	–	–
Armor Stone	–	348	468	383	541
Concrete Cubes	–	612	531	612	612
Tribar	–	–	347	–	401
Lagoon Side					
Riprap	303	356	499	392	–
Concrete Block	573	–	–	–	–
Concrete Rubble	617	–	–	–	–
Armor Stone	–	313	468	348	541
Concrete Cubes	–	556	531	556	612
Tribar	–	–	347	–	401

The availability and cost of landfill materials would be a major consideration for large-scale raising of land elevation. For example, the cost of locally available landfill material is $15/cu. yd. (February 1992), but the local supply is very limited. It is estimated that landfill material would have to be imported, even just to elevate the entire Study Area 1. Imported material would be more expensive. Study Area 1 is less than a square mile; consequently to raise the land roughly by 1 meter or 1 yard would cost approximately $40-50 million. There would be additional costs of temporarily moving homes and buildings in order to allow for the elevation to take place. If such a strategy were to be chosen, this would require long-term planning and capital outlay over many years. The highway and roads would need to be elevated as well, so this requires perhaps the longest leadtime to fully implement. The development scenario estimates that the capital value of the physical infrastructure in Study Area 1 would be $3.03 billion. Once again, elevation of land, if a strategy of accommodation is chosen, should be factored into future infrastructure development in the area before it is too late and costly to carry out the strategy.

TABLE 21. COST ESTIMATES FOR RECOMMENDED SHORE PROTECTION (STUDY AREAS 1 AND 3)

Protected Area	**Shoreline Length** (feet)	**Type of Structure Material** (millions of US$)	
		Armor Stone	*Tribar*
	ASLR1 AND THE TYPHOON EVENT		
J-W-Telap	58,000	105	100
Airport	18,000	22	25
Total		*127*	*125*

Protected Area	**Shoreline Length** (feet)	**Type of Structure Material** (millions of US$)	
		Armor Stone	*Riprap*
	ASLR1 AND THE 50-YEAR EVENT		
J-W-Telap	58,000	46	52
Airport	18,000	8	8
Total		*54*	*60*

Protected Area	**Shoreline Length** (feet)	**Type of Structure Material** (millions of US$)		
		Armor Stone	*Tribar*	*Riprap*
	ASLR2 AND THE ANNUAL EVENT			
J-W-Telap	58,000	81	86	64
Airport	18,000	20	22	10
Total		*101*	*108*	*74*

In advance of a major accommodation response in less valued—i.e. less populated—areas, interim accommodation measures are possible through coastal planning and land use management. There would be associated costs for developing and implementing such a program and further educating the public to accept the need for such management efforts. A combination of accommodation and protection is likely for most of the high-value areas of Majuro, and is already being undertaken on an ad hoc basis in response to current conditions and flooding events.

Accommodation, however, can only be accomplished with zoning laws and building codes and some form of land-use controls which do not currently exist in the Republic. While government buildings and government-funded structures can be built appropriately, it is unlikely in the short term that the Marshall Islands will have the ability to regulate how housing is constructed.

Accommodation cannot be fully implemented as a strategy until such authorities and requirements exist. The socioeconomic situation tends to mitigate against this from happening. The need for regulating construction and land use to accomplish accommodation would force the debate on land-tenure reform and the "old way of life." As was pointed out earlier, since independence and rapid urbanization, many things have already changed. New laws have been passed, such as the Coastal Act and controls to protect water quality, etc., but implementing them is still the challenge to the traditional way of life and thinking.

RETREAT

Because of the lack of land and elevation, Majuro Atoll cannot embody the standard retreat strategy (i.e., move gradually back as nature takes its course). Retreat embodies movement to safety whether it is the high ground (natural or man-made) on Majuro or to another nation. Retreat responses for Majuro will require the identification of which portions of the atoll in Study Areas 1 and 2 would be less subject to erosion, inundation, and frequency of flooding events. The best sites should be selected, and new structures, such as schools or other public facilities, should be designed to serve as shelters and built to withstand a major event. A network of such areas could progressively be established on Majuro as well as on the other islands.

Retreat must also be considered in a strategic sense (i.e., more than a temporary evacuation response). If ASLR2 conditions or worse appear, and flooding disasters make living on the island such that the risks become too great after all has been done to protect against storm surge, then retreat to permanent safety zones may be required. Retreat in the years to come may occur in phases, such as Marshallese moving from the outer atolls (and islets) to the more urban centers, and last, to other nations for refuge. This would be the most drastic measure required and should not be necessitated under the lower projections of ASLR. The greatest factor that would necessitate such measures (at least during the next 50 years) could be related to other climate change factors, such as a shifting of typhoon "alleys" that would put life at risk no matter the protection measures taken. Certainly, both the rate of sea level rise once established for the area and storm patterns will need to be monitored.

Full retreat, if necessitated by worsening conditions of ASLR, would entail more than 73,500 people for Majuro Atoll and 165,000 for the entire Republic, as projected by the development scenario. The population size would be four times greater than currently exists.

NO RESPONSE

Land is already a precious resource in the Majuro Atoll, as in the rest of the Marshall Islands. With projected population growth, land will be even a scarcer commodity. It is difficult to imagine that there will be no response to the existing situation, which already requires a planned, coordinated response to address wave run-up, overtopping, and flooding events, with or without ASLR. No response would lead to the continued loss of land, either 140 (8.6 percent) or 450 (28 percent) acres for the four study areas along with its subsequent socioeconomic impacts.

The no response option would eventually lead to an abandonment (retreat) option because of the continuous loss of land and increased hazards. The option may appear to be the only option for relatively sparsely inhabited small islets with very little land resources or infrastructure, such as those islets located in Study Area 4. These are representative of the outer islands in the Marshall Islands and response measures would require relatively large economic and institutional resources. These are mostly subsistence fishermen or farmers so they may be a little more flexible in moving from area to area. The importance of land areas, even small islets, in future population and development scenarios may be such that a response is warranted.

IMPACTS OF RESPONSES ON NATURAL SYSTEMS

PROTECTION

The major impact of implementing a protection response strategy described in Table 21, would be to protect the land from serious erosion and provide the flood protection benefits.

There would even be the likelihood that additional land could be created through shoreline straightening and backfilling. No such estimate is available. From Table V-2, the estimate of dry land lost for Study Area 1 is 50 acres (10%) and 160 acres (30%) under ASLR1 and ASLR2 respectively. For Study Area 3, 15 acres (6.5%) and 50 acres (22%) respectively. So from $54 to $127 million, depending on the event designed for, you save from 65 to 210 acres out of a total 740 acres.

There will be negative effects of implementing a protection strategy which should be considered and minimized where possible. The construction of shore protection structures will effectively alter the shoreline from a sediment coast of reef-derived sand, rubble and blocks to a rocky coast of revetment or sea walls. Shore protection structures already cover a significant portion of the Majuro coast and some of the environmental impacts from these can be seen, including the loss of sand beaches, aesthetics, and the associated impacts of more coral mining or sand removal which is often used for providing protective structures. If people do not maintain their sea walls and they start to fall apart, the pieces may accelerate erosion to other parts of the shoreline nearby. The proper design and construction of shoreline protective works must accompany the implementation of any major protection strategy to provide that sediment budgets, circulation from ocean to lagoon, etc. are factored in.

ACCOMMODATION

The raising of land elevation to accommodate ASLR would probably be undertaken with shore protection in the same location. The lack of unique or endemic species reduces the possibility of adverse impacts to the overall biodiversity of the Marshall Islands.

If the extraction of local reef, lagoon, or other atoll materials is to provide the fill for raising land elevation, this would result in the loss of this other category of land.

RETREAT

Retreat responses that involve the reinforcement of less vulnerable areas will involve the same impacts as protection and land raising. A response strategy of total retreat—i.e. abandonment—will not affect natural systems other than those resulting from ASLR and natural processes.

NO RESPONSE

With no response to ASLR, erosion and flooding will have considerable impacts, especially on shoreline and terrestrial systems. Chronic and large episodic erosion events will result in loss of land and terrestrial habitat. Ad hoc landfill and shore protection efforts will most likely continue, with their associated impacts. Inundation will also affect terrestrial vegetation and ground water. Impacts from unplanned responses to erosion and flooding may be greater than a planned response that takes into account the environmental aspects of response measures.

VULNERABILITY ANALYSES

SOCIOECONOMIC IMPACTS

The major impacts of implementing the most likely strategy of defense against the sea to protect lives, property, and sovereignty should be mostly economic. Defensive structures are not new, and much of Majuro is already defended, some with very substantial works, and others that are temporary homemade solutions. The costs of well-designed structures including land elevation, run into the millions of dollars. Cost estimates, not including inflation, for recommended shore protection for Study Areas 1 and 3 run up to $127 million to design for ASLR and a typhoon event. This would provide the greatest protection during the next 50 years, but should ASLR2 occur, such protection may still be insufficient. Add $50 million to elevate land and the estimated base cost becomes $175 million. Since this is more than four times the current annual GDP, it is clear that a future construction program would have to be spread out over many years. Even over a 30-year period ($6 million/yr.), this would be cost prohibitive for the economy as described earlier. At the same time, protection is not an all-or-nothing proposition. Priorities can be established and goals achieved, particularly with outside assistance.

Other real concerns have been expressed about the potential impacts of ASLR that cannot be easily resolved. The projected responses to ASLR will have pronounced socioeconomic implications and will exacerbate further social and economic change because the Marshallese life style is so closely associated with nearshore and coastal zone resources. Changes in water resources, potential loss of arable land to erosion—particularly in undefended areas—increased hazards to life and property, and probably some foregone economic opportunities could be expected.

Freshwater resources would be reduced if there is an associated loss of land due to erosion in Study Area 2 as a result of saltwater intrusion of the Laura freshwater lens. This would be a serious matter, as all sources of fresh water for a growing population will be critical to the well-being of the citizens. If population growth doesn't force the issue early on, the nation would be forced to pursue more costly options to supplement their water supply. But water rationing and desalinization plants to supplement water supply are not new to the Marshall Islands. The issue will become more one of cumulative impacts resulting from multiple factors.

Population growth, together with a shrinking land mass due to ASLR, would exacerbate the already large increase in population density. Urban Majuro features one of the highest population densities in the world, which has lead to new and severe social consequences. Further crowding of the population into protected or less vulnerable areas will necessitate reform of the land tenure system, as measures will need to be taken that may go against the traditional system. According to traditional Marshallese life style, the extended family lives in a one-story dwelling. Local foods, including yams, taro, bananas, and coconuts, are cultivated on family land. If population is concentrated in protected and less vulnerable areas, it will be impossible to accommodate these aspects of the Marshallese life style. Access to the ocean for canoes and fishermen will be affected by shore-protection structures. While this may not be a major concern to a large segment of the population, which has already become more urbanized, it would be important still to the traditional subsistence Marshallese population.

The loss of arable land and resulting increased reliance on imported foods can be expected to grow as sea level rises. The Marshall Islands import the majority of their foodstuffs, with over 40 percent of GDP going to their purchase. Urbanization and the reliance on foreign aid have undermined the traditional subsistence system, especially on Majuro. One needs to consider the entire Marshall Islands and not just the study areas in understanding the impacts of ASLR on the Marshallese society and economy.

INSTITUTIONAL IMPLICATIONS OF RESPONSE OPTIONS

Existing institutions for environmental management are inadequate for planning and implementing adaptive responses to ASLR. Strengthening the Environmental Protection Authority, the Office of Planning and Statistics and the Marine Resources Authority will be necessary to cope with expected coastal and nearshore changes. The National Disaster Committee, which regularly meets when storms are in the area, is already well organized, and will have to be expanded to assist in response to ASLR. The National Environmental Management Strategy has identified a number of institutional deficiencies to include better environmental impact assessment planning, needs for zoning and building standards, better coordination between development and environmental management activities, and the difficulties the traditional land tenure system presents in dealing with western-style management efforts. Planning for ASLR becomes one of the many issues that are coming to the fore, just as the newly created agencies and institutions are starting to get organized.

Several other legal and institutional implications spring from the response strategies.

CHALLENGE TO SOVEREIGNTY

The potential for loss of sovereignty associated with the extreme case of total retreat (abandonment) is of deep concern to the Marshall Islands. A recent survey of Marshallese leaders indicated that a guarantee of sovereignty would be necessary before they would willfully relocate to a foreign nation. It is unlikely however, that this option would be fully necessary under the given ASLR1 scenario and the existing governments strategy to protect against erosion and storms. Severity of storms under ASLR2, however, could force relocation for safety reasons alone, so this remains a viable concern.

REFORM OF LAND TENURE SYSTEM

As 100 percent of the land in the Marshall Islands is privately held, and the government does not have authority to use the land without the owner's consent, new legal arrangements will be needed to allow the government to implement response option. For example, it may be necessary to establish public easements along the coastline. The concentration of the entire population in protected or less vulnerable areas may force fundamental land reforms. For example, the relocation of displaced inhabitants from outer islands into the protected areas and the creation of land on the lagoon side will result in land and migration issues in a manner and at a scale not yet experienced.

IMPLEMENTATION OF THE COAST CONSERVATION ACT

A comprehensive coastal zone management plan created under the Coast Conservation Act of 1988 and long-term technical assistance to develop and implement such a plan are needed to integrate the several coastal issues that are linked with impacts and responses of ASLR.

SHRINKING OF EXCLUSIVE ECONOMIC ZONE

The potential for the loss of maritime boundary base points, and consequently the loss of area in the Exclusive Economic Zone, is of great concern. A nation composed of over 99 percent water, the Marshall Islands is increasingly looking to its pelagic marine resources and the deep sea bed. The potential for submersion of one or more of the atolls, and the consequent loss of claim to pelagic and deep-sea resources, would economically disadvantage the Marshall Islands.

COORDINATION OF INSTITUTIONAL RESPONSE

The coordination of studies on ASLR, and the implementation of response strategies require interagency effort at the policymaker level. The Task Force on Environmental Management and Sustainable Development should be expanded to oversee programs related to ASLR and climate change, as is called for in the National Environmental Management Strategy, 1992–96.

CONCLUSIONS AND RECOMMENDATIONS

The analysis of the vulnerability of four case study areas on Majuro to ASLR and extreme events reveals that all land areas are highly vulnerable to major physical impacts—i.e. wave overtopping and flooding. These impacts are severe under ASLR1, when combined with 50-year and typhoon conditions and under ASLR2 under normal weather conditions. Therefore, with the level of information available as applied in this case study, all four study areas investigated would be considered to be highly vulnerable under these scenarios. While well-designed protective structure would go a long way to reducing this vulnerability, the potential costs of constructing such works, even for a few of the most important areas on just one out of 34 atolls, tend to ensure that they will remain highly vulnerable, unless some additional assistance (technical, financial, legal) would be available in the years to come.

A more detailed application of vulnerability assessment methodology developed specifically for the atoll context would allow a more precise indication of vulnerability. Nonetheless, the case study has presented information on the socioeconomic and natural system aspects of each study area, which allows relative priorities to be set for response action in each study area.

PRIORITIES FOR RESPONSE ACTIONS IN THE STUDY AREAS

STUDY AREA 1

Overall priority for response action—High

Rationale—High population and population density; center of commerce, infrastructure development (sea transport, telecommunications) and government; no special natural system land or marine values; high level of shore alteration and protection.

STUDY AREA 2

Overall priority for response action—High

Rationale—Land available for resettlement due to low population and population density; critical ground-water resources; low economic land-use value; important agricultural land use; provides some of the safest area against flooding on atoll.

STUDY AREA 3

Overall priority for response action—High

Rationale—Location of essential airport infrastructure; critical rainwater catchment and storage system; critical communication link between Study Areas 1 and 3.

STUDY AREA 4

Overall priority for response action—Low

Rationale—Very low population and population density; no major economic land-use value.

The risk of potentially serious flooding events which exists both now and would certainly increase in the future should be of paramount concern if lives and property are to be protected. Minimizing the effects of erosion, particularly in areas needed to satisfy the needs of an expanding population, will require proper planning and substantial capital outlays in the future. Many parts of the Marshall Islands may be unsafe to live on because of almost annual flooding events in the future if appropriate protection measures are not taken. Consequently, some areas may have to be abandoned unless future structures are designed to withstand the more serious flood event.

The following sections present issues the Marshall Islands may want to consider in future deliberations and planning for the environmental needs of the Republic. They follow the analysis provided by the Common Methodology. Table 22 summarizes the constraints, which are largely economic and technical.

LEGISLATIVE/INSTITUTIONAL/ORGANIZATIONAL ISSUES

COASTAL ZONE MANAGEMENT PLANNING

National legislation (Coast Conservation Act, 1988) mandating the development and implementation of a Coastal Zone Management Plan already exists, although a plan and its regulations and procedures have not yet been drafted. The specific purpose of the legislation is to protect and preserve "the coast from sea erosion or encroachment of the sea" and to manage the "development activity within the Coastal Zone." While the RMI Environmental Protection Agency is responsible for the Act, it has no technical, financial or human resources dedicated to developing or implementing a plan. The baseline information, time series data, long-term studies, and data management tools needed for developing an integrated Coastal Zone Management Plan that incorporates ASLR are generally not available. There is a particular need to undertake detailed vulnerability analyses of the Marshall Islands, using methods developed for the atoll context.

- Establish, staff and train a Coastal Zone Management Unit within the RMI Environmental Protection Agency Seek assistance through the Pacific Island Network,

TABLE 22. CONSTRAINTS RELATED TO IMPLEMENTATION FEASIBILITY

IMPLEMENTATION ASPECTS	PROBLEM	PARTIAL PROBLEM	NO PROBLEM
VA-LIO: Legislative/Institutional/Organizations			
Level A:			
- existing legislation re CZMP			X
- existing institutions/organizations in CZMP		X	
- executive powers for CZMP			X
Level B:			
- specification of tasks & responsibilities		X	
- communication structure		X	
- staffing/facilities	X		
- existing CZMP plan, regulations, control, etc.	X		
Level C:			
- staff education level	need		
- knowledge & management capabilities	trained		
- staff motivation & working conditions	staff		
VA-ECF: Economic and Financial			
Level A:			
- national economic bearing capacity (ASLR2 Full Protection)	X		
Level B:			
- national funding potential	X		
- regional funding potential		X	
- international funding potential		X	
Level C:			
-financial management capability		X	
VA-TEC: Technical			
Level A:			
- technical knowledge & experience	X		
- technical institutions	X		
Level B:			
- operational structures	X		
- staffing and facilities	X		
Level C:			
- staff education level	X		
- technical qualification/capability	X		
- staff motivation	X		
- data availability	X		
VA-CSO: Cultural & Social			
Level A:			
- cultural constraints	X		
- socio-economic constraints	X		
Level B:			
- cultural programs	X		
- socio-economic programs		X	
Level C:			
- recent cultural achievements			X
- recent socio-economic achievements			X

Note: Level A: Institutional constraints
Level B: Operational constraints
Level C: Quality constraints (effectiveness)

South Pacific Regional Environmental Programme, or other organizations willing to provide such assistance.

- Conduct coastal resource inventories and prepare coastal resource atlases, as have been done for Arno and Majuro Atolls. Seek funding assistance as appropriate.

- Draft a comprehensive Coastal Zone Management Plan that contains a hazards mitigation element.

- Develop a methodology to include monitoring to determine site-specific vulnerability of low-elevation islands to ASLR.

- Conduct vulnerability analyses for all of the Marshall Islands as a basis for incorporating ASLR into coastal management planning and developing response options.

- Assemble the baseline information, commence the time-series data collection, start long-term studies and develop data management tools, as detailed below.

- Develop and implement the permit system in order to start improving the types of development occurring along the shoreline, including the quality of shore protection means, considering elevation of structures, etc.

ENVIRONMENTAL PLANNING AND MANAGEMENT

Although environmental planning and management in the Marshall Islands is starting to make significant strides forward in many areas of concern to the islanders, more will need to be done to deal with responses to ASLR. The relevant agencies and mechanisms for environmental planning and management will need to be strengthened to cope with projected effects of climate change.

- Expand and strengthen capabilities of RMI Environmental Protection Agency.

- Strengthen the capabilities of Office of Planning and Statistics to undertake environmental planning.

- Strengthen the capabilities of sectoral resource agencies (marine resources, agriculture, etc.) to incorporate environmental planning and management into resource development.

- Ensure interagency mechanisms for environmental coordination to incorporate climate change and ASLR into environmental planning and management considerations.

- Expand the role of the National Task Force on Environmental Management and Sustainable Development to include climate change and ASLR in National Environmental Management Strategy development and implementation.

- Implement the RMI National Environmental Management Strategy Action Plan.

INTERNATIONAL AND REGIONAL INTERACTION

Human and financial resources are limited within low-elevation, small island states including the Marshall Islands. It is very important that regional coordination be fostered to ensure an exchange of information, coordination of studies and assistance, maximum multiplier effect and to minimize duplication and overlap. Relevant regional organizations, such as the South Pacific Regional Environment Programme can be used to assist in their coordinating and clearinghouse role. International agencies and donors need to coordinate input and assistance on climate change and ASLR activities with each other and regional coordinating units. In-country agencies have a responsibility to assist coordination by keeping regional and international organizations aware of activities that may require coordination so that they may benefit from what other nations are doing in the Pacific.

- Strengthen ties with relevant regional organizations, and use their coordinating role to assist in meeting Pacific community's needs.
- Ensure coordination of international and donor assistance on climate change and ASLR activities in small island states.

ECONOMIC/FINANCIAL

DEVELOPMENT AID AND INVESTMENT

Much of the economic development activity in the Marshall Islands is driven by assistance from international organizations and multilateral development agencies or through bilateral aid. Projects funded by these sources may not always require the incorporation of sound environmental planning and management. Climate change and ASLR may not be taken into consideration at this time. Current and future flood hazards should be taken into account to protect the project but also serve as potential evacuation shelters. Potential investment in development in Marshall Islands may be deterred by projections of ASLR effects.

- To the extent possible, require development projects funded by outside loans or aid from whatever source to include consideration of existing flooding and erosion hazards as well as ASLR in design and construction parameters, particularly major projects (e.g., roads, school buildings, port berths) with long project life, as well as including sound environmental planning and management. A number of new buildings (museum, justice, and capitol buildings) have been elevated and set a good precedent.
- Develop a sound coastal defense plan and coastal development policy that will encourage sound development projects.

FINANCIAL CAPACITY TO DETERMINE AND IMPLEMENT RESPONSE OPTIONS

To develop the types of shore-protection structures to withstand design storms and ASLR over the next 30-50 years would require a large part of the Marshall Islands budget in relation to the GDP which is largely dependent still on outside assistance. Many difficult trade-offs will need to be made, as well as priority setting. But even then, the assessment assumes a declining GDP as the population increases and the demands for government assistance increase. Majuro Atoll and many of the other RMI islands will remain highly vulnerable if additional assistance (financial and technical) is not obtained in the future to conduct the types of activities to reduce the vulnerability.

- Consider the hazards element within the RMI budget as well as seek outside assistance for the studies, vulnerability analyses, and planning required to determine ASLR response options for the Marshall Islands.

- Begin to consider the long-term capital expenditure needs of shoreline protection measures, and set priorities for the areas needing attention. Establish a long-term goal to seek to obtain the support required for the implementation of ASLR response options.

TECHNICAL ISSUES

DATA COLLECTION AND ASSESSMENT

In order to better predict the impacts of ASLR, a baseline understanding of the natural and human systems is required, as well as information on changes in these systems over time. To understand changes that result from ASLR, it is necessary to separate out other effects, both natural and anthropogenic, on natural and human systems. In addition, tools to effectively handle the data, conduct modeling and make predictions are also required.

- Conduct the inventories, assessments and estimates called for in the Coast Conservation Act to begin to provide the types of information important for future decision making as it relates to coastal erosion and sea encroachment. This vulnerability assessment identified a number of data gaps that required many assumptions and generalizations to be made. Better assessments in the future can be made only if the data is available (bathymetry, topography, etc.). There will be a concern to extend the analysis to other islands, even those less populated than Majuro and Ebeye, and while extrapolation of the results of this study may serve in assessing the other areas for broad-scale planning purposes, future studies as deemed necessary should be site-specific.

- Consider the long-term freshwater needs of the growing population and the role of the freshwater lens in Laura. Monitor ground water for determining status and trends in ground-water quantity and quality. Factor in the diminution of the lens due to various ASLR scenarios in order to begin planning for supplemental water needs, which is likely to occur prior to serious saltwater intrusion, based on population growth rates and the potential for overdrafting. Clearly, the two factors should be considered together.

- Consider establishing an environmental data system for collecting and collating data for environmental monitoring, planning, and management that can also be used in future response planning.

- Conduct surveys for determining kinds, amounts and availability of shore protection and landfill materials in Majuro and the Marshall Islands and identify future sources.

- Attempt to establish the best source of data and model projections for the impacts of regional climate change and future sea level rise, which may be significantly different from the global change projections used in this case study.

PLANNING AND RESPONSE FOR EXTREME EVENTS

Extreme events such as typhoons or storms with near typhoon speeds already affect the Marshall Islands. Drought also affects vegetation as well as the drinking water-system. While the Marshall Islands has a National Disaster Committee to plan for and coordinate disaster response, there is a need to plan for measures to reduce or mitigate their impacts. People living on atolls are always subject to a certain degree of risk from storms, with very few places to find protection, but proper planning and actions can help in saving lives and property.

- Improve capabilities for warning all citizens about tropical cyclones (floods), including disaster response planning and disaster relief following damage from tropical cyclones, storm waves, and tsunamis.

- Determine and implement the best options for securing a safe, reliable and adequate water supply for Majuro in the face of water shortages and lowered water quality during drought and salinization of ground water due to wave overwash or reduced rainfall.

- Develop and apply a methodology for determining the relative vulnerability of areas for retreat.

- Investigate methods, feasibility and costs of raising structures to better accommodate flooding events.

DEVELOPMENT PLANNING AND PROJECTS

Existing development activities and planned developments are affected by extreme events, especially extreme wind and wave conditions. These effects will most likely be exacerbated due to ASLR. Development activities and plans can begin now to take into account ASLR and possible increased extreme event frequency and intensity as a cost-effective, precautionary measure.

- Require shoreline structure design and construction to include parameters for the ASLR projected during the structure's life, through environmental impact assessments and permit procedures.

- Require all publicly funded development activities and private developments that are insured under public insurance schemes to include ASLR in design and construction parameters.

- Ensure land-use planning that takes into account ASLR, and develop required setback limits for different kinds of planned land use. Investigate how better land-use planning can fit within the land-tenure system of the Marshall Islands.

- Through environmental impact assessments and permit procedures, require that the creation of new land by filling in reef flat areas ensures: (1) landfill sites are compatible with land use planning that accounts for ASLR and (2) landfill design and construction include ASLR.

- Ensure that environmental impact assessments and permit procedures require reef flat quarry and lagoon sand dredging site selection and operations (i.e., extraction depth and area) to not exacerbate impacts of ASLR and extreme events.

NATURAL SYSTEM ADAPTATION CAPABILITIES

The ability of natural systems to adapt to ASLR is being compromised by human impacts on these systems. This is particularly important for shoreline sediment systems, coral reefs, mangroves and sea grass beds. Precautionary action can be taken now to maintain the capacity of these systems to adapt to ASLR to their best ability. These actions are also necessary in any case as part of more general environmental management required to ensure the sustainability and maximum productivity of these natural systems.

- Maintain coastal water quality for coastal habitats, especially coral reefs.
- Prohibit destruction of live coral reef and mangrove communities.
- Require adequate protection of coral reef communities during development activities (e.g., dredging, coastal construction), especially from effects of turbidity and sedimentation.
- Regulate beach sand removal for construction purposes.

CULTURAL/SOCIAL ISSUES

GEOPOLITICAL CONSIDERATIONS

The partial loss of land in the Marshall Islands may lead to loss of base points for EEZ boundaries, which could reduce Marshall Islands EEZ territory with its important pelagic and sea bottom resources.

- Achieve an international agreement on land loss due to ASLR and possible EEZ change through the framework of the Law of the Sea.

LAND AND POPULATION PRESSURES

Only the parts of the Marshall Islands may be able to be protected from the impacts of ASLR, which given the ASLR2 scenario would make some islets or atolls unsafe for permanent habitation. In such a case, those areas that are protected or saved for habitation will have to accommodate more people, either through the creation of more protected land or the use of new housing (i.e., high-rise dwellings). This would exacerbate the rapid urbanization problems associated with an already rapid rate of population growth, which has led to a number of environmental management and social problems for the Marshall Islands. The loss of land and creation of new land will complicate the land-tenure situation in the Marshall Islands.

- Undertake studies to determine potential new sites for urban growth, including potential new protected landfill areas for immigrants who must leave because of extremely hazardous living conditions. While such a study may be required to satisfy current growth and migration patterns, the potential for larger-scale abandonment 30 or 50 years away may be of a higher order.
- Investigate the implications of land loss and land creation to the land-tenure system.

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ASSESSMENT OF THE VULNERABILITY OF MAURITIUS TO SEA LEVEL RISE

Vasantt K. Jogoo
Institute of Coastal and Marine Studies
Rutgers University—The State
University of New Jersey
New Brunswick, New Jersey

ABSTRACT

This study quantifies the natural, cultural, and economic elements threatened by future sea level rise in Mauritius. Essentially, the land surface (referred to as the risk area) between mean sea level and +2 meters will be scrutinized from available maps and photographs to produce aerial, linear, and unit measurements of the elements at risk.

This study has been supported by the U.S. Environmental Protection Agency, and carried out under the direction of Dr. N.P. Psuty of the Division of Coastal and Environmental Studies, Institute of Coastal and Marine Sciences, Rutgers University, New Jersey. U.S.A. It complements a preliminary study carried out for the island by Dr. I. Fagoonee, of the University of Mauritius, who made a preliminary assessment of the potential effects of a global warming-induced sea level rise and provided an overview of the institutions and agencies that are involved in coastal land use and resource management.

BACKGROUND

Mauritius is located at latitude 20°south and longitude 58° east about 1,500 miles off the east coast of Africa. The country is of volcanic origin, formed through three main lava flows starting some 9 million years ago, with the last flows ending some 20,000 years ago. The topography is mountainous, peaking at 817 meters, and 50 short rivers and rivulets empty into a shallow lagoon fringed by coral reefs.

Within a decade, Mauritius has moved from a low-income monocrop economy based on sugarcane to that of a more diversified, export-oriented and middle-income status. It is now poised to become the first African "tiger" and join the ranks of the NICs.

Mauritius has about 310 km (200 miles) of coastline, of which about one-third is characterized by good-quality, sandy beaches. Lying within the tropics, it has long hours of sunshine daily, a bilingual well-educated population, and good air links with much of Europe, South and East Africa, South Asia, and the Far East. The combination of these advantages and an effective economic development strategy have helped expand the tourist industry into the third major foreign currency earner (Table 1).

TABLE 1. CONTRIBUTION OF TOURIST INDUSTRY TO FOREIGN EXCHANGE EARNINGS

Activity	**% Contribution to Foreign Exchange Earnings**		
	1974	*1985*	*1990*
Sugar Industry	86	42	26
Industrial Sector	8	46	57
Tourism	6	12	17

The sandy beaches themselves are part of the lagoon system made up of coral reefs, the lagoon proper, and the shore. The coral reef is 150 km long and forms a continuous ring, except in the south and the west, which are characterized by a cliff shoreline. The presence of numerous predators, higher rates of pollution originating on land, and overexploitation of the corals have contributed to the death of a large proportion of the coral reefs. In fact, along certain portions of the reefs, only about 35 percent live corals occur, with a minimum of 1 to 5 percent in the Baie du Cap and Blue Bay areas, while the highest proportions of 60 percent live corals are very limited.

The lagoons cover an area of about 240 square kilometers, usually 1 to 2 meters deep, reaching depths of 10 to 15 meters in the Mahebourg area. These lagoons support a sand-mining industry, providing 450,000 tons of sand annually to the construction industry, and a livelihood to about 30 families. Artisanal fishing in the lagoons is very limited.

The sandy beaches are generally composed of coral sand or coral/basaltic mixtures and are found as pocket beaches or longer stretches of sand. The protected shallow waters of the lagoon encourage depositional action of the waves. However, these sandy beaches are being increasingly subjected to erosion, and future sea level rise may threaten them further—particularly when the protective action of the reefs has been nullified (by continued death of corals or their inability to keep pace with the rate of sea level rise).

The coastal areas of Mauritius have witnessed dramatic changes during the past decade due to the growing importance of the tourist industry in the island's economy. The number of hotels has increased significantly (Table 2), as has the number of secondary residences, driving the price of property to levels unimagined just a few years ago. Also, with the growing affluence of Mauritians, the use and significance of coastal areas in terms of recreational facilities and conservation value have increased remarkably.

TABLE 2. DEVELOPMENT OF THE TOURISM INDUSTRY BY NUMBER OF BEDS AND TOURIST ARRIVALS

Year	**# of Hotels**	**# of Rooms**	**# of Beds**	**# of Arrivals**
1981	51	2,201	4,484	121,620
1982	51	2,204	4,530	118,360
1983	55	2,300	4,900	123,820
1984	54	2,488	5,102	139,670
1985	55	2,630	5,387	148,860
1986	56	2,888	5,955	165,310
1987	60	3,108	6,418	207,560
1988	64	3,399	7,005	239,300
1989	67	3,605	7,374	262,790
1990	75	4,603	9,572	291,600

Tables 3 and 4 show land ownership in the coastal areas and the best approximation of coastal land use available from the Ministry of Housing, Lands, and Town and Country Planning.

TABLE 3. LAND OWNERSHIP IN COASTAL AREAS (KM)

Ownership	Frontage	% of Total Frontage
Private	42.18	13.90
"Pas Geometriques"	250.20	82.53
Harbor Area	10.75	3.54
Total	*303.13*	*99.97*

TABLE 4. COASTAL LAND USE (KM)

Use Type	Frontage	% of Total Frontage
Residential		
Campements	52.0	16.1
Building	25.0	0.8
Services	15.2	4.7
Hotels	29.0	9.0
Beaches		
Declared	11.2	3.5
Undeclared	7.7	2.4
Farming		
Crops	23.7	7.3
Gazing	17.0	5.3
Vegetation	103.7	32.2
Roads	16.1	5.0
Total	*300.6*	*93.3*

METHODOLOGY

Three types of measurements were carried out: aerial, linear, and unit. The sources of data were primarily 1:2500 maps compiled in 1980 from aerial photographs taken in 1978 (Appendices A and B show sample maps). These maps show the mean sea level and contours at 2-meter intervals. Although 129 sheets cover the coastal areas of Mauritius, only 103 maps were pertinent to this study as the rest cover areas that have cliff coasts.

The 1:2500 maps have been supplemented by aerial photographs taken in 1990 for parts of the coastal areas (Port Louis to Cap Malheureux, covering the Northern Tourist Zone). Further, spot checks have been carried out wherever possible.

The area between mean sea level to high-tide line (referred to as Zone I) is public domain, and no development is either allowed or possible in this zone, whether it is privately or publicly owned. No separate account, therefore, is presented for this particular zone.

AREA AND RESOURCES AT RISK

The total risk area is approximately 1,028 hectares, as shown in Table 5. (Appendix A tabulates the areas at risk in detail.) Since the total area of Mauritius is 186,494 hectares, about 0.5 percent of the territory is directly threatened by projected sea level rise.

TABLE 5. TOTAL AREA AT RISK

	Area in Hectares
Subtotal 1	147.53
Subtotal 2	108.90
Subtotal 3	213.33
Subtotal 4	259.96
Subtotal 5	148.97
Subtotal 6	149.40
Grand Total	*1,028.09*

HOUSING

Table 6 shows that an estimated 1,205 housing units will be partly or totally affected by projected sea level rise. Detailed tabulation of the units at risk is presented in Appendix B.

TABLE 6. TOTAL HOUSING UNITS AT RISK

Housing Units Totally Affected	1,092
Housing Units Partly Affected	13
Total Housing Units Affected	*1,205*

POPULATION

From the housing figures, it is possible to deduce the population directly at risk (Table 7). It is assumed that the household size is 4.7 (the national average) and that each unit houses one household. The total population at risk is, therefore, 5,663, or about 0.5 percent of the island's population.

TABLE 7. POPULATION AT RISK

Total Housing Units Affected	1,205
Household Size (1990)	4.7
Total Population Affected (1,205 x 4.7)	*5,663*

TOURIST INDUSTRY

The destruction of beaches in Mauritius will seriously affect the tourist industry. Almost 95 percent of all hotel rooms are located along the coastal zone on about 575 acres. Further, of the projected 2,127 new hotel rooms, 1,957 (Table 8) have a coastal location. Therefore, any adverse impact on any one of these elements can seriously jeopardize the future of the tourist industry.

The tourist industry employs 9,670 people (1990, in establishments employing more than 10 persons in hotels and restaurants only). Total employment generated by the industry may be double that number if all other tourism-related activities are considered (car rental, tourist shops, small restaurants, guest houses, etc.). The total number of people employed in Mauritius in 1990 was 396,098.

Some major hotel chains have already invested in beach-protection schemes, with a good measure of success. The Sun International Group has used geotextile screens to protect its beaches, with minimum damage to the lagoon's ecosystem, and over the past two years, the beaches have advanced seaward about 50 feet.

TABLE 8. PROPOSED HOTEL PROJECTS

Name of Project	# Rooms	Location
Desnyland Village Ltd	30	Pte D'esny
Cilaos Beach Resort	40	Trou D'eau Douce
Palmar Resorts	30	Palmar
South Seas	180	Baie Aux Tortues
Holiday Village	64	Wolmar
Sun Tan Hotels	40	Palmar
Dynasty*	150	Colline Monneron
Albion Investment	150	Albion
Seaside Leisure	40	Pte Aux Piments
Belle Mare Beach Devt.	170	Belle Mare
Sunesta	190	Wolmar
Belle Mare Investment	124	Belle Mare
Miramar	120	Wolmar
Motel Du Nord	30	Pereybere
Mtius Trading Contractg.	100	Le Morne
Tamarin Bay Resort	300	Tamarin
Beach Holiday	29	Belle Mare
Ramjuttun & Co	156	Pte Aux Canonniers
Sun N Sand	52	Mont Choisy
Coronation Hotel	112	Flic En Flac
Minmetals *	20	Floreal

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* Hotels located in urban areas.

FURTHER STUDIES

Further quantification of natural resources at risk are required. The topograpghical sheets and aerial photographs available do not indentify specific resources, so that field checking will be necessary. This will require much more time and a larger staff. It is estimated that a further U.S. $10,000 will be necessary to mobilize the necessary staff and complete the study.

APPENDIX A: AREA AT RISK

Sheet #	Area in Ha.	Sheet #	Area in Ha.
2080	4.05	8276	4.84
2695	3.20	8284	2.43
2689	7.65	8497	2.84
2699	3.32	8496	1.32
2698	1.12	7672	3.91
2896	5.45	8291	2.75
8802	3.83	8286	3.55
0219	2.00	8290	1.58
1811	2.06	8073	7.66
9811	1.04	2206	8.59
2205	14.81	2203	5.22
2075	2.45	2207	13.41
1872	17.38	2403	2.10
8801	3.02	2404	0.83
2080	2.61	0017	2.12
1421	3.79	9812	11.67
1023	2.18	9813	1.77
7870	9.79	9814	1.67
7872	12.88	9815	5.55
8285	3.58	9816	7.69
8281	6.95	0016	1.86
8278	1.51	0666	2.21
8279	31.48	2204	12.20
8277	1.38	0867	1.13
Subtotal	*147.53*	*Subtotal*	*108.90*

Sheet #	Area in Ha.
2075	5.10
2073	2.89
8283	2.81
1616	10.81
8287	22.04
8492/8292	2.63
8485	9.83
8486	6.26
8698	1.88
8072	5.25
7671	20.36
8072	5.35
0265	
8495	2.25
8280	51.51
Subtotal	*148.97*

Sheet#	Area in Ha.
2074	2.88
8289	19.66
8282	2.81
7670	68.27
8288	22.38
8479	1.06
8487	
8494	1.61
8493	1.48
7871	
8697	
8600/8601	2.66
8699	4.25
8070	22.34
Subtotal	*149.40*

Sheet #	Area in Ha.
0665	4.10
0866	3.66
0465	1.97
0264	3.35
0064	1.79
9265	3.26
9266	0.25
1416	7.74
1021	9.76
1418/1618	11.18
1417	1.35
1614	14.67
1022	9.70
9609	1.88
0623	4.86
0823	4.01
1420/1620	13.10
1613	11.86
1419/1619	38.74
1810	10.99
1221/1222	41.45
0219	2.10
0220	1.73
0221	3.63
0420	6.20
Subtotal	*213.33*

Sheet #	Area in Ha.
0421	2.20
0622	18.33
1617	7.28
2401	1.03
2694	6.83
1877	10.58
2400/2600	1.51
0218/0018	28.59
1671	3.70
1678	6.54
1873	1.44
8274	2.50
8275	6.70
8478	4.83
9810	1.75
2693	7.29
2691	4.22
2209	
2208	2.66
2010	48.12
7873/7673	37.90
2897	3.16
2690	5.65
1880	37.23
1876	9.92
Subtotal	*259.96*

APPENDIX B: HOUSING UNITS AT RISK

Sheet #	Totally Affected	Part Affected
2080	-	-
2692	-	-
2695	6	-
2689	21	-
2699	-	-
2698	-	-
2896	-	-
8802	-	-
8801	-	-
0219	-	-
1811	-	-
9811	-	-
2205	-	-
2075	-	-
1872	-	-
9806	-	-
8801	-	-
2080	-	-
1421	2	6
9203	-	-
1023	-	-
SUBTOTAL	*29*	*6*

Sheet #	Totally Affected	Part Affected
7870	-	-
7872	-	-
8285	23	-
8281	-	-
8278	-	-
8279	18	-
8277	-	-
8276	-	-
8284	-	1
8497	-	-
8496	-	-
7672	8	1
8291	-	-
8286	-	-
8290	-	-
8073	2	2
2206	10	2
9265	3	-
0623	11	6
8274	26	4
8275	37	12
8478	7	2
SUBTOTAL	*145*	*34*

Sheet #	**Totally Affected**	**Part Affected**
9810	-	-
9402	-	-
9665	-	-
9808	91	5
2693	-	-
2691	-	-
2209	38	2
2208	-	-
2010	109	7
7873	9	-
2897	-	-
2690	12	-
1872	2	-
1880	6	-
1876	100	-
2075	-	-
2074	-	-
2073	4	-
8289	30	-
8283	7	2
8282	-	-
SUBTOTAL	*408*	*20*

Sheet #	**Totally Affected**	**Part Affected**
7670	-	-
8287	-	-
8288	-	-
8492	-	-
8479	-	-
8485	77	10
8487	-	-
8486	5	-
8494	-	-
8698	-	-
8493	-	-
8072	-	-
7871	-	-
7671	-	-
8697	-	-
8072	-	-
8600	-	-
0265	-	-
8699	-	-
8495	-	-
8070	-	-
SUBTOTAL	*82*	*10*

Sheet #	Totally Affected	Part Affected
8280	12	1
2401	-	-
2694	2	-
1877	43	7
2400	-	-
0218	35	-
1671	-	-
1678	-	-
1873	-	-
1420	16	-
1613	-	-
1419	9	7
1810	7	-
1221	27	3
0219	-	-
0220	-	-
0221	-	-
0420	11	13
0421	-	-
0622	250	12
SUBTOTAL	*428*	*43*

APPENDIX C: ROADS AND SERVICES AT RISK

Sheet #	Roads (Km)	Services & Amenities
2080	130	-
2692	-	-
2695	60	-
2689		Ferry Boat Office, Jetty Shelter, Altar for Worship
2699	-	-
2698	-	-
2896	-	Livestock Breeding Station
8802	-	-
8801	-	-
0219	-	-
1811	-	-
9811	-	-
2205	-	-
2075	-	-
1872	-	-
9806	-	-
8801	-	-
2080	-	-
1421	-	-
9203	-	-
1023	-	-
7870	-	-

7872	-	-
8285	-	Swimming Pool, Pump House, Home for Handicapped, Post Office, Dispensary, Village Market, Fish Coop
8281	460	-
8278	304	-
8279	-	-
8277	20	-
8276	135	-
8284	-	-
8497	-	-
8496	-	-
7672	360	-
8291	-	-
8286	-	-
8290	-	-
8073	-	-
2206	450	Fishery Post
9265	-	-
0623	-	Public Space
8274	-	-
8275	170	-
8478	250	-
9810	-	-
9808	900	-
9803	-	-
2691	-	-
209	680	-
2208	-	-
2010	-	Church
7873	2000	Bank, Boat House, Tennis Court
2897	1080	-
2690	400	Tennis Court
1872	430	Tennis Court
1880	450	-
1876	1030	Public Garden, Children's Playground, Movie Theater, Station, Health Office, Market, Fish Landing Station
2075	-	-
2074	730	Sailing Club
2073	-	-
8289	1010	-
8283	-	-
8282	-	-
7670	1280	-
8287	850	-
8288	1040	-
8492	-	-
8479	-	-
8485	840	-
8486	-	-
8494	-	-
8698	-	-
8493	-	-

8072	-	-
7871	-	-
7671	750	-
8697	90	-
8072	700	-
8600	-	-
0265	-	-
8699	-	-
8495	-	-
8070	1230	Forestry Quarters, Fish Landing Station
8481	-	-
8071	-	-
8280	2565	-
2401	-	-
2694	-	-
1877	900	Welfare Center, District Council Office, Registry, Monument, Fountain
2400	1450	-
1671	-	-
1678	-	-
1873	-	-
1420	450	-
1613	-	-
1419	970	Altar for Worship
1810	210	-
1221	430	Kiosks (2), Swimming Pools (4) Football Ground
0219	-	-
0220	-	-
0221	-	-
0420	-	Church, Mosque
0421	-	-
0622	1505	Cafetaria, Lavatories (2)
0218	1050	Boat House, Post Office, Banks (2), Corner Shop, Golf Course, Tennis Court Taxi Stand, Swimming Pools (2)

ASSESSMENT OF THE VULNERABILITY OF THE KINGDOM OF TONGA TO SEA LEVEL RISE

Netatua P. Fifita
Ministry of Lands, Survey and Natural Resources
Kingdom of Tonga

Nobuo Mimura
Department of Urban and Civil Engineering
Ibaraki University, Japan

Nobuyuki Hori
Department of Geography
Tokyo Metropolitan University
Japan

INTRODUCTION

The Coastal Zone Management Subgroup (CZMS) of the Intergovernmental Panel on Climate Change (IPCC) proposed a new program, at the IPCC Plenary on March 1992, to examine the vulnerability of coastal nations to accelerated sea level rise. Responding to this proposal, a study was established for Tonga under the collaboration of Tongan and Japanese researchers. The objectives of this study are:

- To assess the vulnerability of Tonga to sea level rise, focusing on Tongatapu Island, using the Common Methodology proposed by the CZMS.
- To identify problems specific to and important for small coral islands.
- To provide a basis for the future study of response strategies and comprehensive coastal zone management.

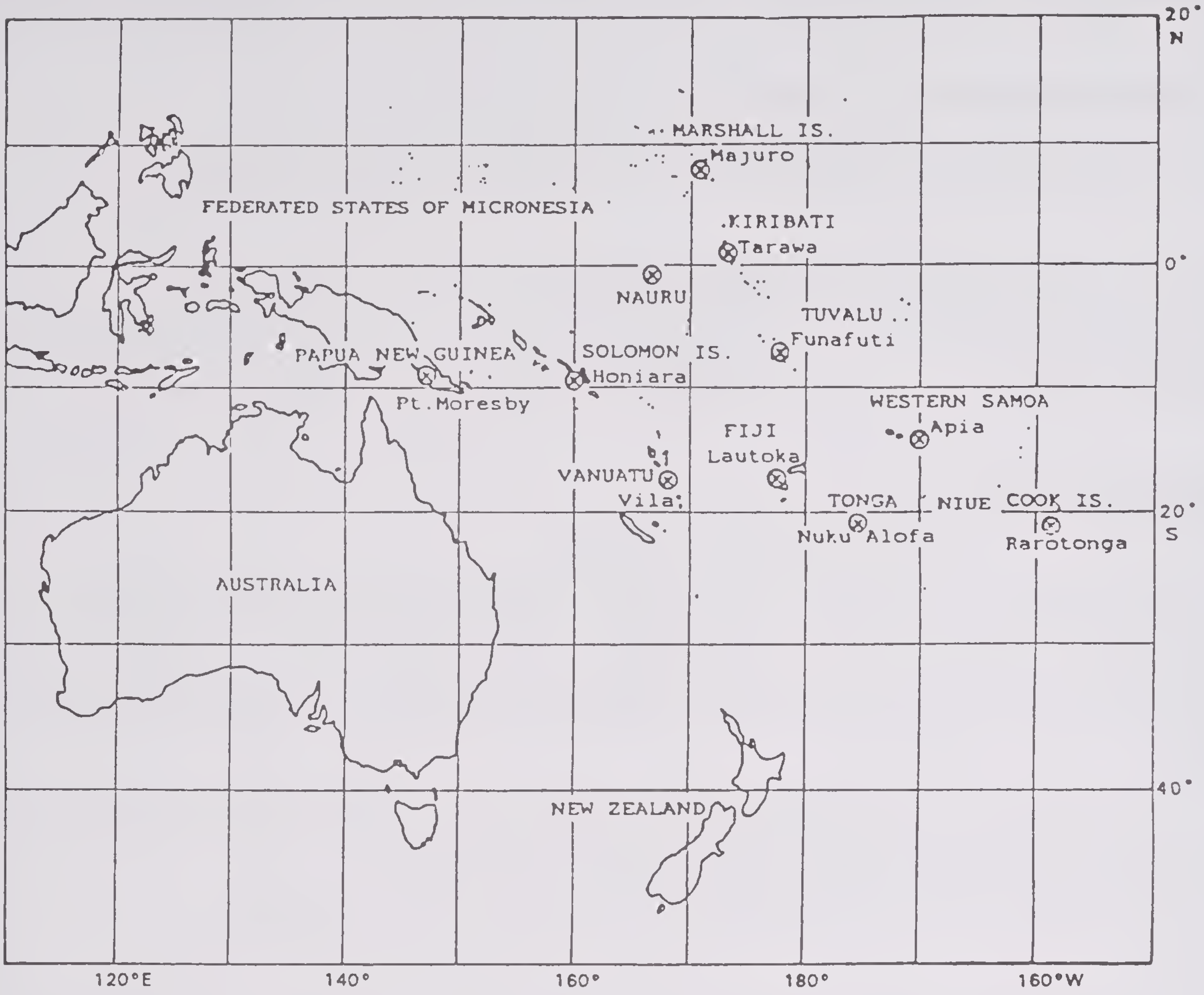
This study has been performed mainly based on existing materials, such as reports of the government of Tonga and international organizations, and academic publications. Field surveys were also conducted to gather information about the required depth of the assessment. In addition, a new topographic map with 1-meter contours up to an elevation of 5 meters was developed for Tongatapu Island. Possible impacts from inundation and flooding were evaluated by using this map. This report describes the results obtained thus far by integrating the existing knowledge and the new findings of this study.

GEOGRAPHICAL AND GEOLOGICAL BACKGROUND

The Kingdom of Tonga is located in the South Pacific Ocean between 15° and 23.5° south latitude and 173° and 177° west longitude, as shown in Figure 1. This places Tonga about 1,700 km northeast of New Zealand and about 700 km southeast of Fiji.

The islands of the Kingdom of Tonga are scattered across 360,000 km^2, and each has a wide range of variety in natural conditions. Tonga's total land area is 747 km^2. There are about 171 named islands, but only 36 are permanently inhabited. The largest is Tongatapu, which is the site of Nuku'alofa, the capital. Six islands comprise three-quarters of the land area and contain 90 percent of Tonga's population of 94,649 (1986 Census).

FIGURE 1. GEOGRAPHICAL POSITION OF TONGA



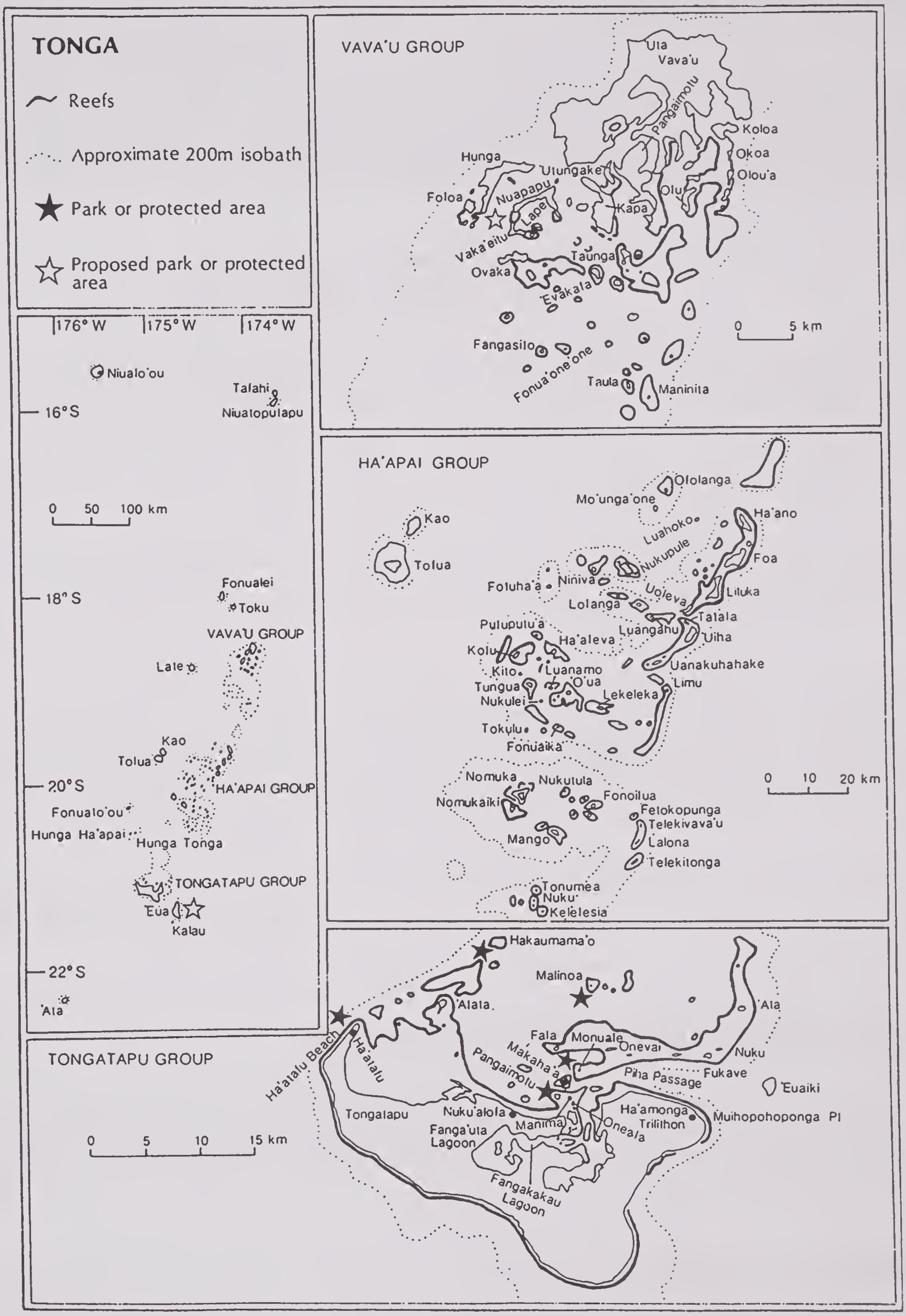
The islands of Tonga extend 560 km in a NNE-SSW direction, as shown in Figure 2. They are commonly divided into four groups: the Niuas, the Vava'u Group, the Ha'apai Group, and the Tongatapu Group.

Easily accessible, shallow-water reefs and shoals (less than 10 meters deep) cover about 550 km^2, while an additional 3,045 km^2 constitute sea floor within the 200- meter shelf. Tonga, therefore, can be considered to have about 1,200 km^2 of readily accessible land and marine resources, 3,000 km^2 of marine resources more difficult to use, and a pelagic and deep-water zone of about 393,000 km^2 (The Kingdom of Tonga, 1991).

The Tongan archipelago is formed as the western edge of the western Pacific Plate collides with and slides below the Indian/Australian Plate. There are two parallel lines of islands: the western line consists of volcanic islands, and the eastern line, coral islands. East of the coral islands is the deep Tonga Trench, which extends at times to a depth of 10,500 meters.

The islands of Tonga are composed of fresh volcanic islands and uplifted limestone islands. The limestone islands, while founded on older volcanic substrates, are essentially biological constructs closely interlocked with the living fauna and flora. This gives the basic natural condition to the islands of Tonga, which would bring about peculiar impacts from accelerated sea level rise.

FIGURE 2. ISLANDS OF TONGA



Source: "Coral Reefs of the World."

SCENARIOS FOR SEA LEVEL RISE AND OTHER CLIMATE CHANGES

Two scenarios are used for sea level rise, as shown in Table 1: one is 0.3 meters as a lower scenario to be reached in 2100, and the other, 1 meter as a higher scenario. It is desirable to consider the speed of the sea level rise in the assessment. However, since it is very difficult to evaluate the rate of change, the present study neglects time-dependent phenomena and their consequences. This means that the impacts are assessed for the sudden change in sea level.

TABLE 1. BOUNDARY CONDITIONS RELATED TO SEA LEVEL RISE AND CLIMATE CHANGE

Boundary Conditions	Units	SLR1	SLR2
Accelerated rise of sea level due to increase in greenhouse effect	m	0.3	1
Other possible conditions			
Increase in storms			
Change in temperature		No change is assumed	
Change in precipitation			
Change in evaporation			
Change in UV-B radiation			

Climate changes and related physical changes induced by global warming are not limited to sea level rise. For Tonga, for example, the changes in the intensity and frequency of cyclones must have great influence. However, since there is no prediction of these climate changes on a local scale, no changes are assumed for the local climate other than sea level rise.

Another important factor that affects the vulnerability assessment is the future development of the coastal zones. Since it is very difficult to predict the future trend of natural and socioeconomic development of the coastal region, then no development is again assumed in this study.

PHYSICAL CHARACTERISTICS OF THE STUDY AREA

Tongatapu, the largest island of Tonga, is the focus of in this study, since it occupies one-third of the land area and contains 70 percent of the Kingdom's population. The following description mainly concerns Tongatapu, though the paper tries to discuss other islands and the whole of Tonga, where possible.

TOPOGRAPHY OF TONGATAPU

Tongatapu island extends 40 km long from east to west and is 20 km at its widest. It is generally flat, but slopes from a maximum elevation of 65 meters in the southeast to sea level along the northern coast. There the sea penetrates inland to form a large, shallow lagoon, Fanga'uta, that is 27 km^2. Nuku'alofa is located on a flat peninsula between the lagoon and the ocean. Figure 3 shows the topography of Tongatapu. Most of the urban area of Nuku'alofa has an elevation of 0.5 to 1.5 meters above mean sea level, and many parts of the city are below 0.5 meters (Spennemann et al., 1988).

Since the islands of Tonga are on the edge of an active plate, strong uplift may occur. However, Taylor and Bloom (1976) have concluded that there has been no net uplift or tilting of the Tongatapu Group at least in the last 125,000 years. Therefore, relative sea level change due to crastal motion is not a priority for study, compared with the speed of the anticipated sea level rise.

NATURAL AND ARTIFICIAL COASTS

Tongatapu has broad tidal flats, coastal swamps, and mangrove forests along the northern edge. A narrow fringing reef surrounds the east, south, and west coasts. Coral reefs extend northward from the north coast of the island along an extensive submerged terrace. Between the two coral ridges is a large harbor with deep entrances from the north and the east. The extensive shallow lagoon in the central part of the island is Fanga'uta. Mangrove forests fringe the lagoons and the north coast of Tongatapu.

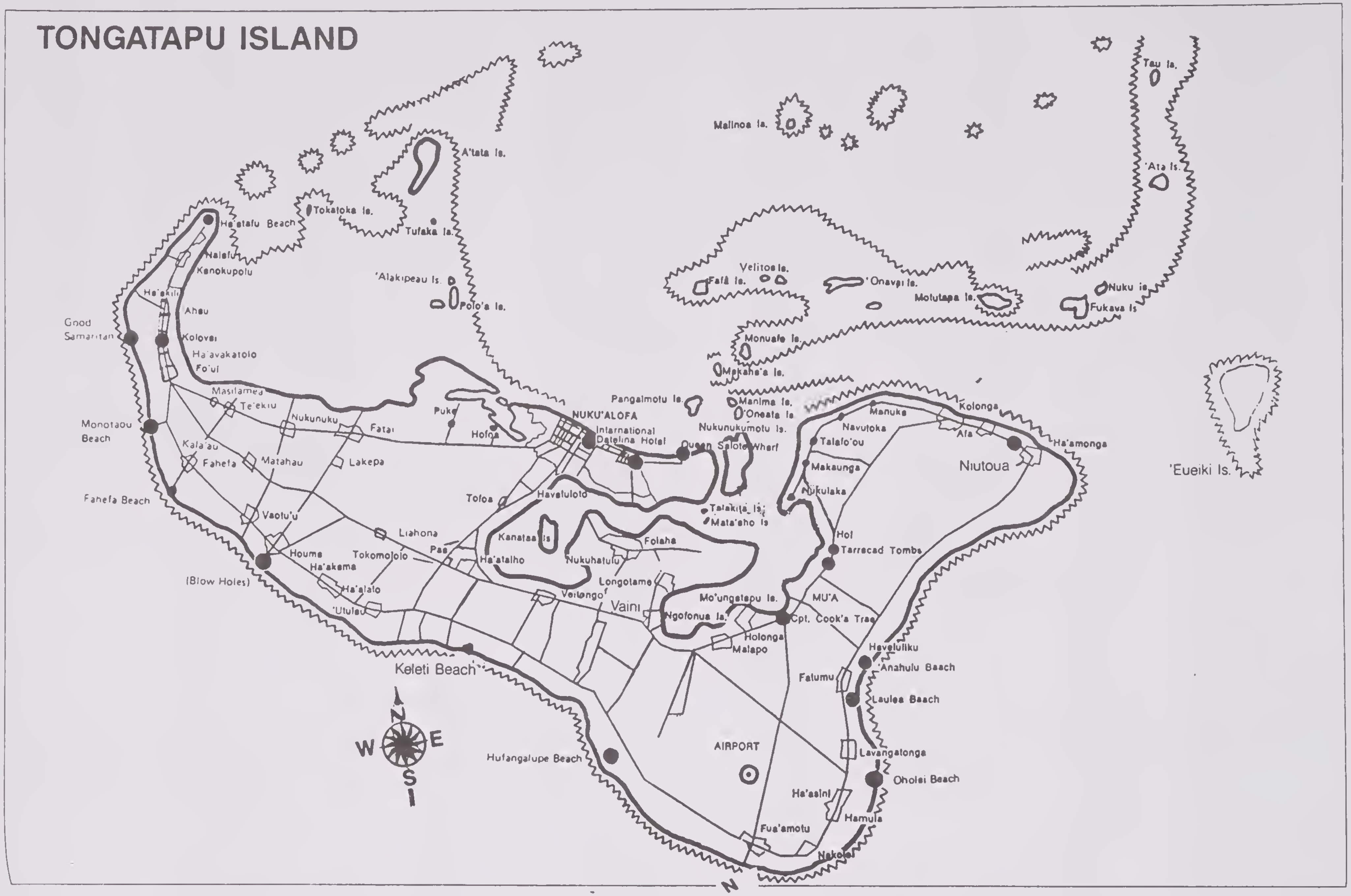
Tongatapu has more than 10 sandy beaches, some of which are pocket beaches. Many of the popular beach areas have been stripped of sand because of the high demand for construction material, which exceeded the potential for sand regeneration. The length of each type of coast is summarized in Table 2.

Waterfront development in Tonga has been limited to the construction of wharves and jetties adjoining major towns and villages, and housing development in mangrove swamps. The Nuku'alofa foreshore protection was reconstructed following damage from the 1982 cyclone "Isaac." In 1986, 3,400 meters of protective wall were completed. The Queen Salote Wharf complex and the Fauna Fisheries harbor were completed in 1986 and 1987, and two other wharves are on the fringing reef flat at Nuku'alofa.

TIDE AND DESIGN WATER LEVEL

From the existing studies, the tidal range of the spring tide was found to be 1.1 meters for Nuku'alofa. This indicates that the tidal motion at Nuku'alofa is not very strong. As for the design water level, the high-water level induced by a cyclone should be taken into account. A detailed survey was carried out for a maximum water level during the cyclone "Isaac" in 1982, revealing that the water level reached 2.50 to 2.75 meters (above chart datum) over the whole length of approximately 8 km of the north shoreline. On the basis of this survey, an expert concluded that a design water level of approximately 2.8 meters would include most of the risk, which should be considered for design purposes under the current sea level (Ministry of Works, 1983).

FIGURE 3. TONGATAPU ISLAND



After Douglas, N., and N. Douglas, 1989.

WAVES

In designing the foreshore protection work, design wave characteristics were determined by a wave forecast (Ministry of Works, 1983). Winds blowing from the north to the bay in front of Nuku'alofa are usually calm. In addition, toward the northeast and northwest the bay is sheltered by the chain of islands and protected by vast fringing and isolated reefs. Because of such sheltering effects, the significant wave heights, H1/3, can be estimated on the order of less than 0.5 meters under ordinary conditions.

In the case of a cyclone, higher wave height in deep water and rise in sea level due to wave action on the reef should be taken into account. Using a semiempirical calculation for a typical cyclone, the significant wave height was calculated to be approximately 8.8 meters and the corresponding period 11.5 seconds in the offshore region. However, about 2.0 meters were estimated to represent the upper limit of possible wave heights transmitted to the reef by the sheltering effects of the topography.

TABLE 2. NATURAL SYSTEM DATA: PHYSICAL CHARACTERISTICS

Type of Data	Units	Data Value
Coast types (length)		
Natural		
Mangroves	km	60
Sand	km	26
Cliff	km	5
Cliff & sand	km	2
Others	km	74
Artificial		
Sea dikes/sea walls	km	3.4
Others		4 wharves
Local subsidence	mm/yr	Neglectable
Design water level at different locations	m	2.8 (Nuku'alofa)
Average tidal range	m	1.1
Annual average wave climate (Hsig, for morphological aspects)	m	0.5 (Nuku'alofa)
Design wave height (Hsig, for structural aspects)	m	2.0 (Nuku'alofa)
Area with (potential) salinity problems	km^2	-

TROPICAL CYCLONES

One of the most distinctive features of the region's meteorology is the occurrence of tropical cyclones. Although tropical cyclonic disturbances may occur all year round, they are principally confined to the wet season from December to the following April, which is also called the cyclone season. The statistics of cyclones that hit Tonga are shown in Table 3 (Fifita, 1991).

TABLE 3. FREQUENCY OF CYCLONES THAT AFFECTED TONGA

Month	Number of Cyclones		Total
	1830 to 1923	*1923 to 1982*	
January	16	10	26
February	7	13	20
March	17	7	24
April	6	6	12
May		1	1
June			
July			
August			
September			
October	1	1	2
November	4	2	6
December	4	8	12
No record	1	1	2

CYCLONE "ISAAC"

Tropical cyclone Isaac was one of the worst cyclones to hit Tonga in recent years (Crane, 1988). It originated about 290 km north of Niue on March 2, 1982, and passed near Tongatapu Island.

Six people died as a result of the cyclone, and three of the deaths occurred in Ha'apai, where an additional 10 people were seriously injured. Tonga lost 16 percent of its poultry and 8 percent of its pigs in the storm. Cattle and horses were not so badly affected.

The winds were very destructive to tree and fruit crops. An estimated 95 percent of the ripening coconuts in Tonga were blown off the trees. In the Ha'apai Islands, 20 percent of the coconut trees were uprooted or completely stripped of their foliage. Furthermore, 90 percent of Tonga's bananas, 90 percent of its breadfruit, and 40 percent of its vanilla beans were blown from their trees or vines. About half of the root vegetables, such as yams and cassava, were destroyed.

The strong winds tore the roofs from many buildings, and many more were completely flattered. As a result 2,400 houses needed replacing, and nearly 60 percent of them were in Ha'apai. Almost all foreshore protective structures in front of Nuku'alofa as well as the boundary structures of the Army harbor, the Fuau Boat harbor, and the slopes of the wharves were destroyed or have been considerably damaged by cyclone "Isaac."

CYCLONE "OFA"

Tropical cyclone "Ofa," which occurred in January to February of 1990, was one of the most destructive cyclones in the southwest Pacific during the 1989–90 cyclone season.

In Tonga, the worst damages were recorded in the islands of Niuatoputapu (Keppel) and Tafahi, which lay closest to the path of cyclone "Ofa." The meteorological station at Keppel estimated a maximum wind speed of 90 knots. At the same time, Niuafo'ou, some distance away, estimated winds of 44 knots.

Niuatoputapu and Tafahi suffered from severe damage to houses, church buildings, coconut plantations, food crops and other vegetation. Over 70 percent of the families in Niuatoputapu lost their houses completely, with the remaining 30 percent losing their roofs either partly or completely. Over Niuafo'ou, damage was only moderate, and occurred mostly to crops and vegetation. Preliminary estimates of the damage from the cyclone stood at about U.S. $3.2 million.

WATER RESOURCES

Water is one of the most critical resources for the small, isolated, widely scattered islands of Tonga. For most of Tonga's populated island, the main source of water is either rainwater caught on rooftops and stored in cisterns or a thin lens of fresh water in highly porous limestone rock substrata. There are no streams or freshwater lakes on the major islands.

Recharge rates to the lens depend on the amount and distribution of rainfall. Short, light rainfall contributes very little to aquifer recharges, since most is lost to evaporation and transpiration by plants. It is during the prolonged rainfall that sufficient water passes the soil vegetation layer and moves down through the soil and limestone to float on top of the sea water. Figure 4 shows a comparison of the distribution of ground- water salinity between 1971 and 1990 (Furness, 1992). It can be seen that salt water intrudes farther inland in 1990. This may be attributed to the recent drought in Tonga.

In Tonga, the size of the ground-water resource is directly related to the size of the island. Larger islands provide the mass necessary for development of freshwater lenses that are less vulnerable to tidal mixing and have enough storage to sustain withdrawals during extended periods of drought. In contrast, smaller island freshwater lenses shrink during prolonged periods of low rainfall, and water quality is impaired. The estimated water available from the Tongatapu freshwater lens from the average year's rainfall is 40,000 m^3 per day (Central Planning Department, 1987).

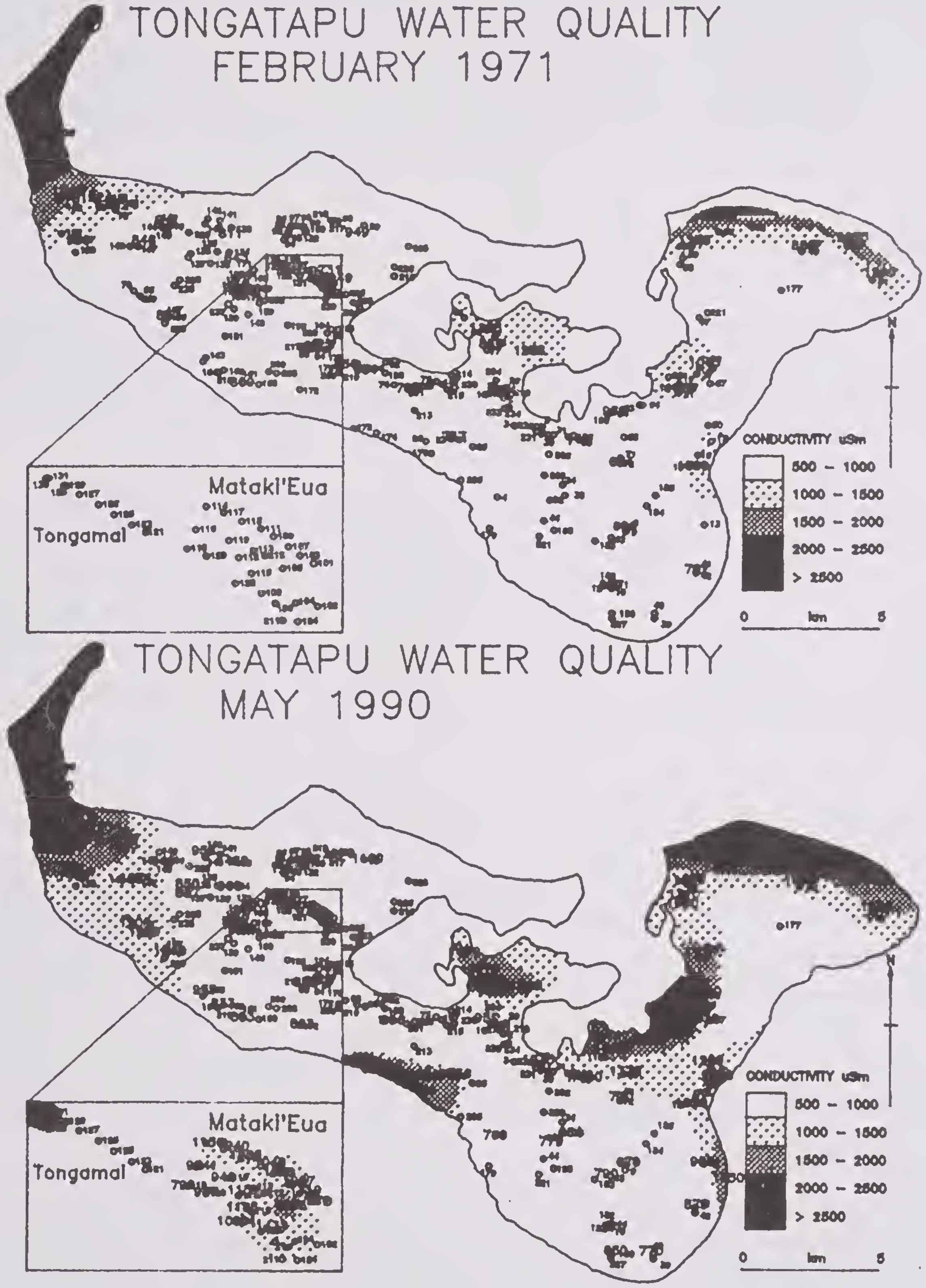
ECOSYSTEMS AND CULTURAL HERITAGE OF THE STUDY AREA

There are various types of important coastal ecosystems around Tongatapu, such as, coral reefs, tidal flats, mangrove forests, lagoons, and sandy beaches. The areas of these ecosystems are summarized in Table 4.

TABLE 4. NATURAL SYSTEM DATA: ECOSYSTEMS

Type of Data	Units	Data Value
Mangrove	km^2	9.4
Coral reef	km^2	(wide)
Lagoon	km^2	37.3

FIGURE 4. DISTRIBUTION OF SALINITY IN GROUND WATER



Numbers in the figures indicate the positions of wells (Furness, 1992).

All areas of shallow-water habitats that are valuable for subsistence fishing are heavily fished. Intertidal flats near villages provide substantial amounts of seafood, while remote reefs are visited by fishermen when weather permits.

Nine ecosystems around Tongatapu are protected areas, and 17 other areas have been designated as Protected Areas or Traditional Areas of Respect. The nine protected areas comprise five national marine parks and reserves, two national historical parks, and two other protected areas.

SOCIOECONOMIC SYSTEMS OF THE STUDY AREA

POPULATION

Tonga's resident population is currently estimated at about 97,000, of which 67 percent live in Tongatapu, and 30 percent in Nuku'alofa. In addition, an estimated 30,000 Tongans live overseas, mostly in New Zealand, Australia, and the United States (The Kingdom of Tonga, 1991)(Table 5).

TABLE 5. SOCIOECONOMIC SYSTEM DATA

Type of Data	Units	Data Value
Gross Domestic Product	lc*	
Population	#People	97,000
Recent average growth rate		
GDP	%/yr	0.05 (1986-1990)
Capital value	%/yr	-
Population	%/yr	0.5 (1976-1986)

---

*Local currency.

Over the past 50 years, the urbanization of the population has been increasing, not only through emigration to urban centers overseas, but also through migration from the outer islands to the Greater Nuku'alofa Area, and from the rural areas of Tongatapu to the capital. The distribution of population in the Kingdom is very uneven, with Tongatapu being the fastest growing, at an average annual rate of 1.1 percent. Assuming that the growth rate was constant over the decade 1976–86, between the two censuses, the average annual growth is estimated at 0.5 percent.

PATTERNS OF ECONOMIC GROWTH

Economic growth has been declining. During Development Plan periods III, IV, and V, spanning the period 1975–90, the average growth rate for each period, respectively, as 3.7 percent, 3.4 percent, and 0.05 percent. Tonga expected to achieve a rate of growth of almost 5 percent during period V, but real GDP growth did not achieve that goal.

In terms of growth, the agricultural sector was stagnant over the 14-year period. Economic growth in most sectors has declined over the period V, to the point where it is almost negative. To a certain extent this is attributable to the lack of growth in the agricultural sector—the largest contributor to GDP.

LAND USE AND COAST-RELATED PROBLEMS

CULTURAL ROOTS AND LAND LAW

Villages in Tonga began as fortifications known as *kolo* during the civil war (1779–1852). Families generally had a small piece of land known as the *'api kolo* (place to reside in town) and an *'api 'uta* (place to garden). This pattern of land use is still in effect today and is one of the major facets of Tongan life and environment.

The Act of 1882 established the right of every Tongan male over 16 years of age to both a town *'api* and a garden (or bush or tax) *'api*. The Land Act of 1927, and its subsequent amendments, forms the legal basis for the land-use system in Tonga. Land distribution is one of the major issues in Tonga today. Increasing population and urbanization have used up the available agricultural and town land. In 1976, 65 percent of eligible people did not have tax *'apis*.

CONFLICTING LAND USE

Because of the rapid population increase of Nuku'alofa, low-lying areas adjacent to the urban center are being reclaimed for housing. The Sopu Lagoon was closed off by dams in 1951 to be used as an agricultural area. However, the constantly wet and saline soils were poor for growing most crops. By the 1980's, much of the old lagoon was used for housing. In 1982, sea surge flooded the lagoon during the cyclone "Issac," causing considerable damage to homes in the area. The government then began allocation of *'apis* in mangrove swamp at Poputa, to the east of Nuku'alofa.

Population increases and migration are forcing the government to supply new land. As all of the useful agricultural land is already allocated, there has been an unfortunate tendency to subdivide and register environmentally sensitive lands and lands with low productivity or hazardous potential.

EXPLOITATION OF CONSTRUCTION MATERIALS

Sand is used to make aggregate for concrete and is also used traditionally as ground cover around houses and to cover graves. The rapidly increasing rate of construction of houses and buildings, using primarily concrete blocks and concrete foundations, has resulted in a rapidly increasing demand for sand.

Sand is surface-mined from the beaches. The amount collected at major sites reached from 820 tons to 2,100 tons. Laulea Beach, one of the sites, currently has a hollow profile. Dunes at the back of the beach have been removed by storms and redistributed onto the beach, but this recharge is not renewable. The fifth five-year development plan claims: "Sand removal from the beaches of all the major island groups will continue to be carefully regulated to prevent the loss of this important tourist, recreational, and environmental resource."

Limestone rock is mined on all the major islands and is used for road construction and maintenance, sand aggregate for concrete, and home and building construction.

PHYSICAL CHANGES CAUSED BY SEA LEVEL RISE

The physical changes caused by sea level rise and global warming-related climate change include:

- Inundation of low-lying lands and coral reefs.
- Exacerbation of coastal flooding.
- Increase in shoreline erosion.
- Saltwater intrusion into ground water.
- Alteration of tidal range.

Among these phenomena, inundation and flooding are the major focus of this report, as they are the most primary physical changes.

TOPOGRAPHIC MAP WITH 1-METER CONTOURS

In order to evaluate the area possibly to be affected by sea level rise and flooding, a topographic map with at least 1-meter contours is necessary. Such a map could not be found in the existing materials, except maps limited to the town area of Nuku'alofa (Belz, 1984). However, a set of airborne photographs was provided for the whole region of Tongatapu. A new map was made in this study to draw 1-meter contours up to the elevation of 5 meters on the basis of these photographs. As the reference level of this map, the 5-meter contour line was taken to correspond to that of the existing 1:25,000 map published by the Tonga government. The 1-meter contour line of the new map was found to be very close to the coastline of the existing map.

Figure 5 shows the relative elevations of various sea levels and the chart datum. The mean high-water level is higher than the 1-meter contour by 0.2 to 0.3 meters for different tidal conditions. However, since no accurate data were found for the positions and elevations of the present coastline, a 1-meter contour based on the chart datum was considered to be a shoreline in the present study. The coastlines and contours were imputed into a computer to evaluate the impacts on the natural and social conditions related to sea level rise.

WATER-LEVEL SCENARIOS

As for the water levels, several scenarios can be drawn. In order to take various situations into account, the following water levels were used in this study.

a. Present mean sea level: 0.75 meter above chart datum
b. High-water level: 1.0 meter above chart datum
c. Extreme event (storm surge): 2.8 meters above chart datum
d. Sea level rise: 0.3 and 1.0 meters

The area below the water level of a storm surge can be considered to be at risk, while the area below the high-tide level may be regarded to be lost by inundation. According to the scenarios of sea level rise, four scenarios of water levels were set to evaluate the area at loss and at risk, as shown in Table 6. For example, if a storm of the highest level would occur with a 1-meter sea level rise, the water level could reach (c) + (d) = 3.8 meters above the chart datum. Even for the ordinary condition, the high-water level would become (b) + (d) = 1.3 meters for a 0.3-meter rise in sea level and a 2.0 meters for a 1-meter rise.

FIGURE 5. SEA LEVELS AND CHART DATUM

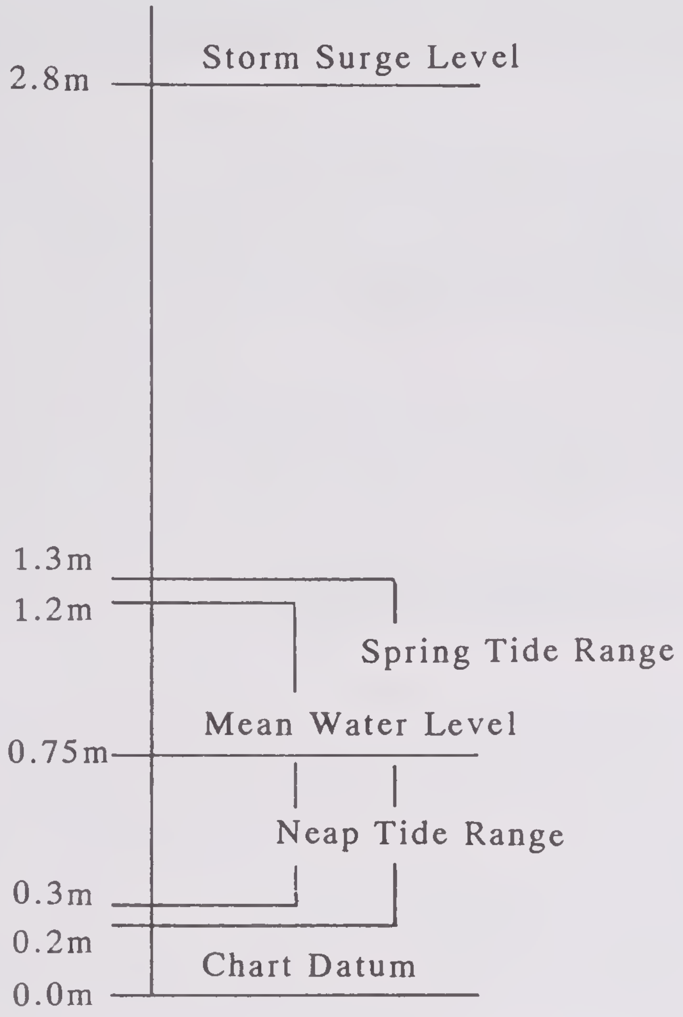


TABLE 6. SCENARIOS FOR WATER LEVELS

	Present Condition (m)	ASLR1 (m)	ASLR2 (m)
Ordinary condition (High-water level)	1.0	1.0+0.3=1.3	1.0+1.0=2.0
Extreme Event (Storm surge)	2.8	2.8+0.3=3.1	2.8+1.0=3.8

---

* Elevations are based on the chart datum. One-meter contour nearly corresponds to the high-water level (i.e. the present coastline).

AREAS AND POPULATIONS TO BE AFFECTED

The location and boundary of towns and villages were superimposed on the contour map in the computer. Figure 6 shows the distribution of residence areas in Tongatapu Island. Since the population of each town or village is given in the 1986 Census, if the percentage of the area affected were known, the population to be affected could be estimated by assuming that the density of population is uniform within a village.

FIGURE 6. DISTRIBUTION OF RESIDENCE AREAS IN TONGATAPU ISLAND

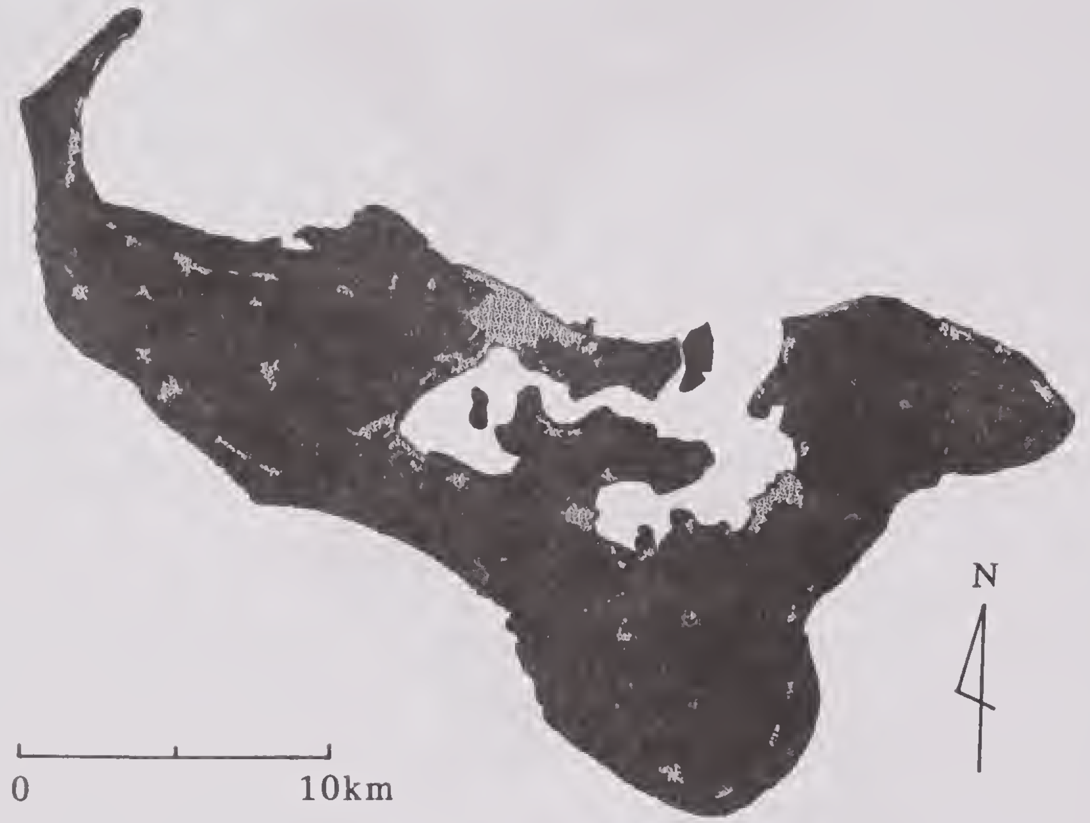


Figure 7 shows the areas below the 2- to 5-meter contours. It can be seen that lowlands extend along the north shore, and that the land elevation is particularly low at Nuku'alofa. The areas and populations below these contours are also listed in Table 7. By interpolating these data, the areas and populations that would be affected by the increases in water level listed in Table 6 were obtained, as shown in Table 8.

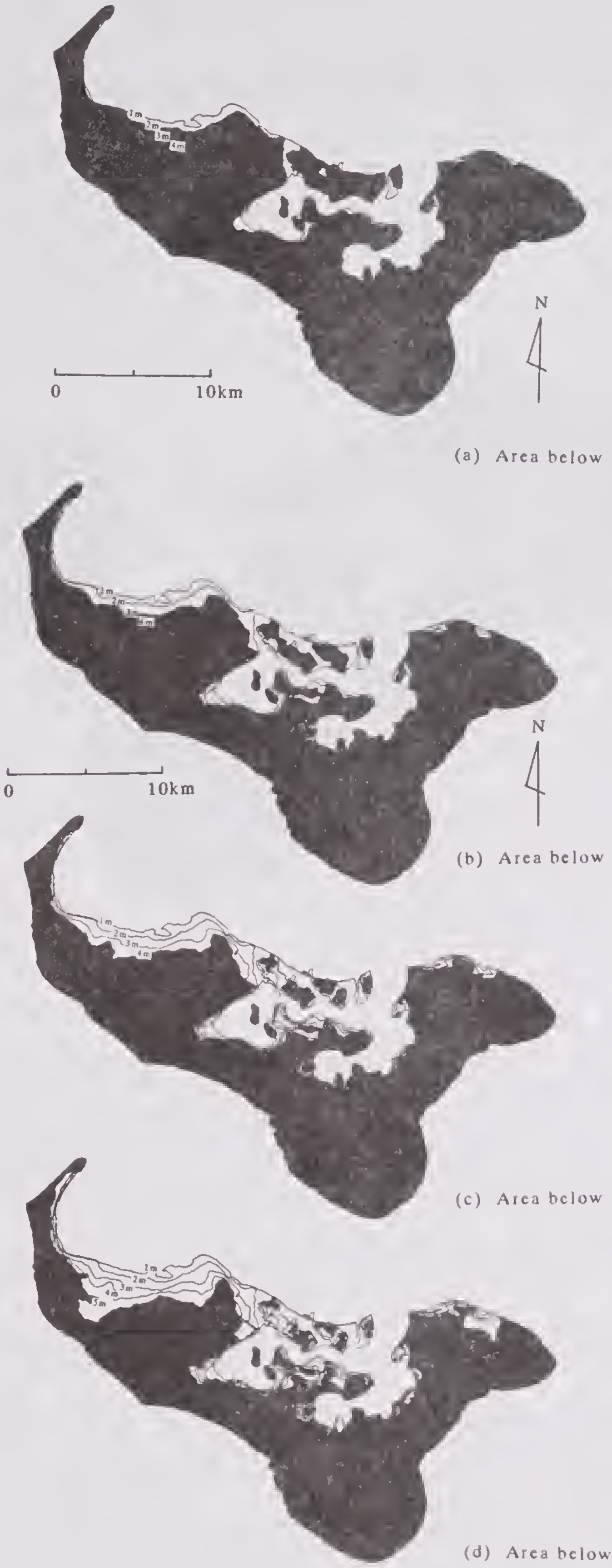
TABLE 7. AFFECTED AREAS AND POPULATIONS

	Whole Land Area		**Residence Area**	
Elevation	Innundation Area (km^2)	Remaining Area (km^2)	Affected Area (km^2)	Affected Population
1m	~0	264.8	~0	~0
2m	10.3 (3.9%)	254.5	2.2	9,000(14.2%)
3m	26.6 (10.0%)	238.2	5.6	22,600 (35.6%)
4m	40.0 (15.1%)	224.8	8.1	31,300 (49.4%)
5m	58.0 (21.9%)	206.8	10.7	40,100 (63.2%)

---

* Percentages of the affected areas and populations are based on the total values of the Tongatapu Island.

FIGURE 7. AREAS TO BE AFFECTED BY SEA LEVEL RISE



(a) Area below 2m contour

(b) Area below 3m contour

(c) Area below 4m contour

(d) Area below 5m contour

Areas to be affected by sea level rise
Elevations in these maps are based on the chart datum.
1-m countour nearly corresponds to the present coastline.

TABLE 8. PHYSICAL EFFECTS OF SEA LEVEL RISE

Impact Categories	Present Situation (0.0m)	SLR 1 (0.3m)	SLR 2 (1.0m)
Values at Loss			
Land area (km^2)	0	3.1 (1.3%)	10.3 (3.9%)
Residence area (km^2)	0	0.7	2.2
Population to be affected	0	2,700 (4.7%)	9,000 (14.2%)
Value at Risk			
Land area (km2)	23.3 (8.8%)	27.9 (10.6%)	37.3 (14.1%)
Residence area (km2)	4.9	5.9	7.6
Population to be affected	19,880 (31.3%)	23,470 (37.0%)	29,560 (46.6%)

---

*Percentages of affected areas and populations are based on the total values of Tongatapu Island.

The 0.3- and 1-meter rises would cause land losses of 3.1 and 10.3 km^2, respectively, or about 1.3 and 3.9 percent of the total area. About 2,700 and 9,000 people would be affected, or 4.3 and 14.2 percent of the total population of Tongatapu, respectively. For the situation of extreme events, about 20,000 people currently live in the low areas that are vulnerable to a storm surge of 2.8 meters. If a storm surge occurs under the 0.3-meter scenario, 27.9 km (11 percent of Tongatapu Island) and 23,470 people (37 percent of the Tongatapu population) would be at risk. These will increase to 37.3 km^2 (14 percent) and 29,560 (46 percent) for the 1-meter scenario. These results show that the impacts of sea level rise would not be limited to inundation; the danger of the cyclone-induced storm surge would increase significantly.

In order to check the accuracy of the estimate, further surveys are necessary for the elevations along the shoreline.

IMPACTS ON SOCIOECONOMIC AND CULTURAL CONDITIONS WITHIN THE STUDY AREA

INCREASE IN DANGER OF EXTREME EVENTS

As mentioned above, one of the most significant effects of sea level rise is the increased danger of extreme events. Sea level rise raises the baseline for storm surges, making it more dangerous to the people and properties on the low-lying areas along the north coast of Tongatapu Island. Moreover, storm surges will be accompanied by higher waves, because the protective function of coral reefs will be weakened as water depths increase. In addition, wave action will become more violent with sea level rise.

Such physical changes will increase the danger of extreme events significantly. Although the shoreline around Nuku'alofa is protected by sea walls, it may become necessary to reexamine the design conditions and to strengthen the protection measures.

IMPACTS ON NUKU'ALOFA

Nuku'alofa is the center of administration and the most highly populated area in Tonga. Even a "static" sea level rise of 1 meter would inundate a part of central Nuku'alofa, owing to the raised ground-water table. Since this would affect most of the residential, business, and administrative districts, it would also affect the efficiency of the government departments. Several government buildings are likely to be flooded. The southeastern area of Ma'ofanga would be isolated, and the roads along the coast would also be affected very severely.

POTENTIAL IMPACTS ON WATER RESOURCES

In the larger islands, water is obtained from the freshwater lens by wells. On small islands, insufficient water is stored, and the inhabitants have to rely on rainwater catchment.

The effect of a rising sea level on the larger, raised coral islands, such as Tongatapu, 'Eua, and Vava'u, would be a corresponding rise in the freshwater lens. This would have little impact on the water supply in most villages. There might be a problem with the plumbing system, when the freshwater lens rises but the pump is still lower, thus drawing up salt water.

In the smaller low-lying islands that use ground water for freshwater supply, a rise in sea level could have a significant impact. The islands of Ha'apai Group would be particularly vulnerable to sea level rise due to their low elevation. The effects would be a reduction in the area of fresh water and local saltwater intrusion into the aquifer.

IMPACTS ON AGRICULTURE AND CROPS

With sea level rise, gardening land would be inundated, and the newly created marginal areas would experience a higher moisture loading and increased salinization, reducing their suitability for gardening. This pressure on land resources will increase even further, as people may need to be relocated from inundated or swamped areas, and additional garden land needs to be converted into housing areas (Spennemann et al., 1988). The effect of saltwater intrusion into ground water is severe for some crops. If sea level rise is accompanied by other climate changes, such as longer dry periods, food production may decrease seriously.

IMPACTS ON SEWAGE DISPOSAL SYSTEMS

Sewage disposal systems will be seriously affected by the rise in sea level. As the water level rises and advances on the sloping shorelines, existing sewage treatment facilities may be inundated.

IMPACTS ON NATURAL COASTS AND ECOSYSTEMS

Sea level rise will exacerbate the erosion of coasts, because of high waves. Increases in water depth along the coral reefs will be accompanied by higher, more forceful waves. Beaches of sand and fine sediments will be eroded. Ecosystems in low-lying areas, such as mud flats and mangrove swamps, may be also vulnerable to inundation, flooding, and wave action. This is anticipated to lead loss of important resources for tourism. Coastal vegetation, which is important for medical use, for cultural use (costumes of traditional dancing and dye for clothes), and as shelters against strong winds, will also be threatened.

IMPACTS ON CULTURAL HERITAGE

For Tongan cultural heritage, which forms a unique part of the world's cultural heritage, the increase in relative sea level will have severe implications, because the future of most archaeological sites is at risk. Two types of damage can be forecast: (1) direct damage caused by inundation and increased tidal activity and (2) indirect damage caused by the destruction of sites as a result of countermeasures to stop the inundation of highly valued land areas.

A relative rise in sea level will greatly increase the need for landfill to heighten the ground level. At present, coral rubble is used for filling low-lying areas at the lagoonal waterfront. About 0.3 to 0.5 meters of coral gravel is applied, upon which a 0.2- to 0.4-meter thick layer of topsoil is heaped. To some extent, this topsoil is quarried from the top areas of newly opened quarries, but also from archaeological sites, notably house and burial mounds. This process, which has started very recently, is likely to continue (Spennemann et al., 1988).

REDUCTION OF LAND AND EXCLUSIVE ECONOMIC ZONES

All Pacific states will be significantly affected through the loss of outlying islands and low-lying areas. Such losses will substantially reduce the sizes of the exclusive economic zones (Fifita, 1991).

POTENTIAL RESPONSE STRATEGIES

The Coastal Zone Management Subgroup of the IPCC examined the response strategies to sea level rise and classified them into three basic categories: retreat, accommodation, and protection. In the present study, however, a systematic examination could not be conducted. Instead, some points will be presented for the future investigation of the comprehensive response strategies.

LAND-USE PLANNING FOR LOW-LYING AREAS

Nuku'alofa, where a large portion of the nation's population lives, is located on a flat peninsula with ground water very close to the land surface and lowland areas, as mentioned above. There are also many villages that are vulnerable to damage from cyclones and storm surges. Careful land-use planning is essential to protect these areas and to avoid the costly protection of cultural resources in future.

Future settlement should not be allowed along the lagoon edges or in any area below 0.5 meters elevation. Settled areas below 0.5 meters should be filled to higher levels, with the exception of the lagoon edge. However, finding fill material may pose a significant problem.

PRESERVATION OF THE COAST'S NATURAL PROTECTIVE FUNCTION

Natural coastal systems, such as coral reefs and mangroves, provide protective functions. Sandy beaches and dunes also protect inland areas from waves and, to some extent, storm surges. Therefore, it is important to preserve these systems. In addition, the current overexploitation of sand from beaches is depleting valuable recreational and tourism resources. Government and private quarries have already begun to manufacture cement aggregates with crushers. The application of such alternatives will eliminate the need to destroy Tonga's limited beaches.

COUNTERMEASURES TO EXTREME EVENTS

One of the countermeasures to sea level rise is raising the foreshore protection wall along Nuku'alofa. Since the impacts of storm surges and waves are estimated to increase, higher sea walls will be necessary to protect the Nuku'alofa area. However, sea walls cannot stop the indirect inundation of low-lying area behind them, because the inundation will result from the rising ground water table in the porous limestone. Moreover, it is anticipated that coastal construction will impose a considerable amount of additional expenditure on the national budget.

COMPREHENSIVE PLAN FOR COASTAL ZONE MANAGEMENT AND NATURAL DISASTER PREVENTION

Tonga has a National Office for Disaster Relief and Rehabilitation. However, it does not have a comprehensive national disaster prevention plan. There are no building standards to require safety construction against cyclones. It is necessary to develop a comprehensive plan for preventing natural disasters and coastal zone management, because the uses, development, natural disaster prevention, and preservation of natural resources have to be managed carefully for sustainable development in the coastal region.

CONCLUSIONS AND RECOMMENDATIONS

Through this study, a part of the vulnerability profile of Tonga was obtained. Coral islands are often divided into low and high islands. And low islands have drawn attention in terms of the impacts of sea level rise. Although Tongatapu is not a typical low island, it is concluded that the impacts of sea level rise are also very significant, owing to Tonga's natural and socioeconomic characteristics: Nuku'alofa, the capital, being located on lowland; the increases in population in Tongatapu; the increasing tendency of people to live in coastal regions; and the overexploitation of beach sand and limestone.

This study, also examined some response options. However, in order to advance toward developing appropriate response strategies to ensure the safety and sustainable development of Tonga, much work will be required, including the following:

- Further assessment of the impacts on socioeconomic and cultural activities.
- Vulnerability assessment of all of the Kingdom of Tonga.
- Development of relevant response strategies.
- Promotion of training programs to build local capability to deal with these tasks.
- Promotion of public awareness programs.
- Identification of areas that need technical and financial assistance.

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CASE STUDIES OF DELTAS

ASSESSMENT OF VULNERABILITY TO SEA LEVEL RISE: A CASE STUDY OF BANGLADESH

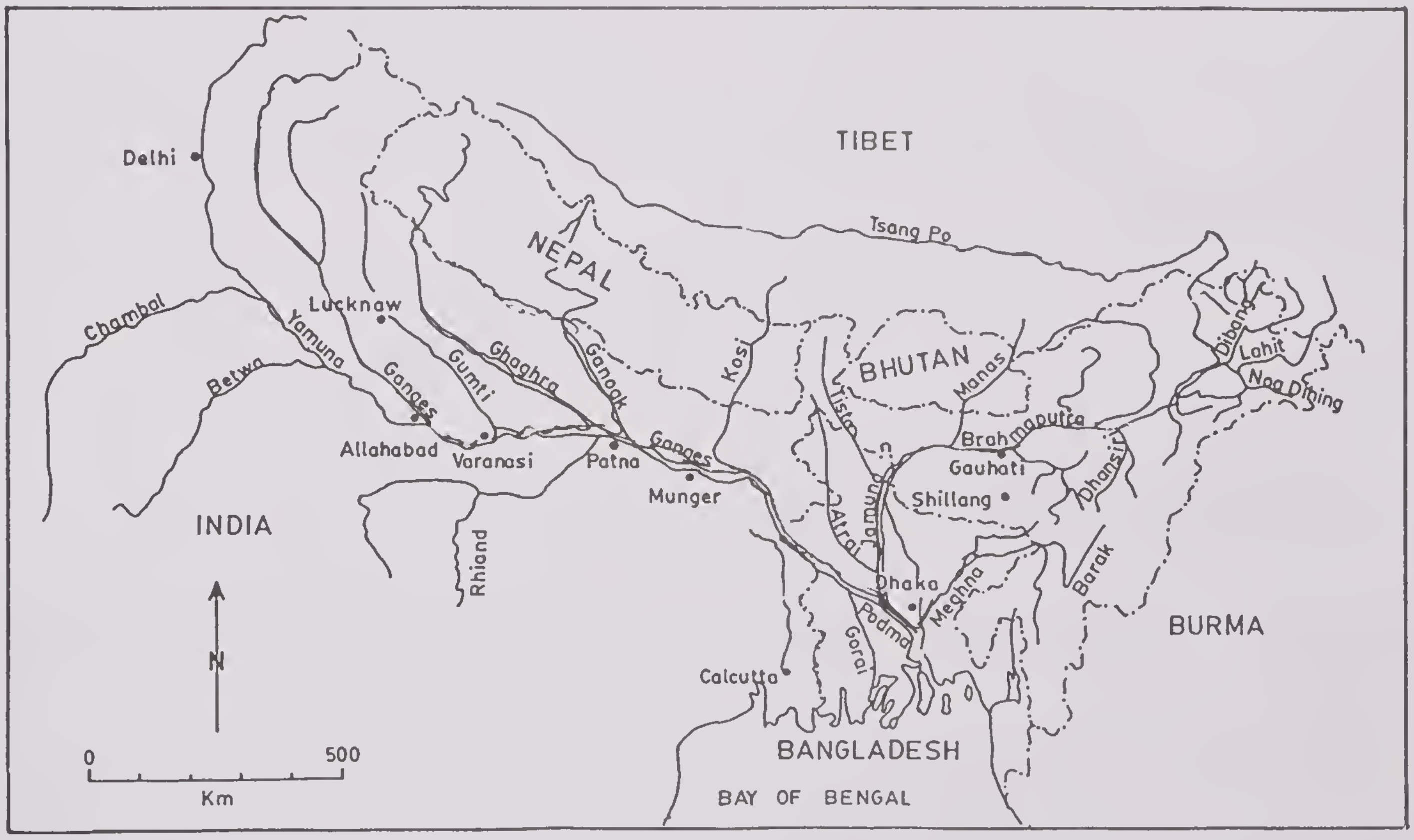
Amjad Hossain Khan
Saleemul Huq
A. Atiq Rahman
M. Shahidullah
A. Haque
Syed Ali Naqi
Mujibur Rahman
Saleh Ahmed
Syed Iqbal Ali
Mohammad Youssouf Ali
Mohiuddin Ahmed
Yusuf Islam
Feroze Mollick

Bangladesh Centre for Advanced Studies
Dhanmondi, Dhaka, Bangladesh

INTRODUCTION

Bangladesh, with a population of over 110 million people living in an area of 144,000 square kilometers, is one of the most densely populated countries of the world. Located on the delta of three of the world's major rivers—namely, the Ganges, the Brahmaputra, and the Meghna—most of Bangladesh is less than 100 meters above mean sea level. Being at the northern end of a major funnel-shaped ocean system of the Bay of Bengal also makes the country susceptible to cyclones and storm surges that periodically are generated in the Bay of Bengal and travel northward hitting the coast of Bangladesh (Figure 1).

FIGURE 1. HIMALAYAN DRAINAGE SYSTEM



Bangladesh is located on the delta of the world's major rivers: the Ganges, the Brahmaputra, and the Meghna.

The main economic activity of the country is agriculture. It provides the major part of the gross domestic product and accounts for most of the country's employment. However, the level of agricultural holdings and productivity is extremely low, with most rural households owning less than 1–2 hectares of land and depending mostly on the annual monsoon rains to grow the main subsistence crop of rice. Bangladesh's low elevation and deltaic nature ensure that the tidal influence goes practically two-thirds up the country from the coast (Figure 2). Bangladesh also has substantial resources of ground water, which is widely used for both drinking and irrigation, and which is influenced by salinity in the coastal areas (Figure 3). Further flooding conditions and the 1-meter sea level rise predicted line (BCAS study) are shown in Figure 3. Bangladesh also suffers periodically from floods caused both by increased downstream flows of the major rivers flowing into the country as well as by extensive rainfall. Such floods can affect up to 65 percent of the country and are a regular and important feature that is sometimes compounded by backwater effects of high tides.

Like the coastline of many countries, Bangladesh is the location of very valuable land and infrastructure. These include the major port cities of Chittagong and Khulna; the major tourist beach at Cox's Bazaar; the world's biggest mangrove forest, the Sunderbans; a number of islands, including a coral island, St. Martins; and extensive shrimp farms and other agricultural areas. All of these areas are likely to be at risk from any increase in sea level.

This paper attempts to briefly highlight some of the likely impacts of a 0.3-meter and a 1.0-meter sea level rise on a number of physical, environmental, and socioeconomic parameters and focuses mainly on the possible response strategies and needs for developing suitable responses.

THE STUDY AREA AND SEA LEVEL RISE SCENARIOS

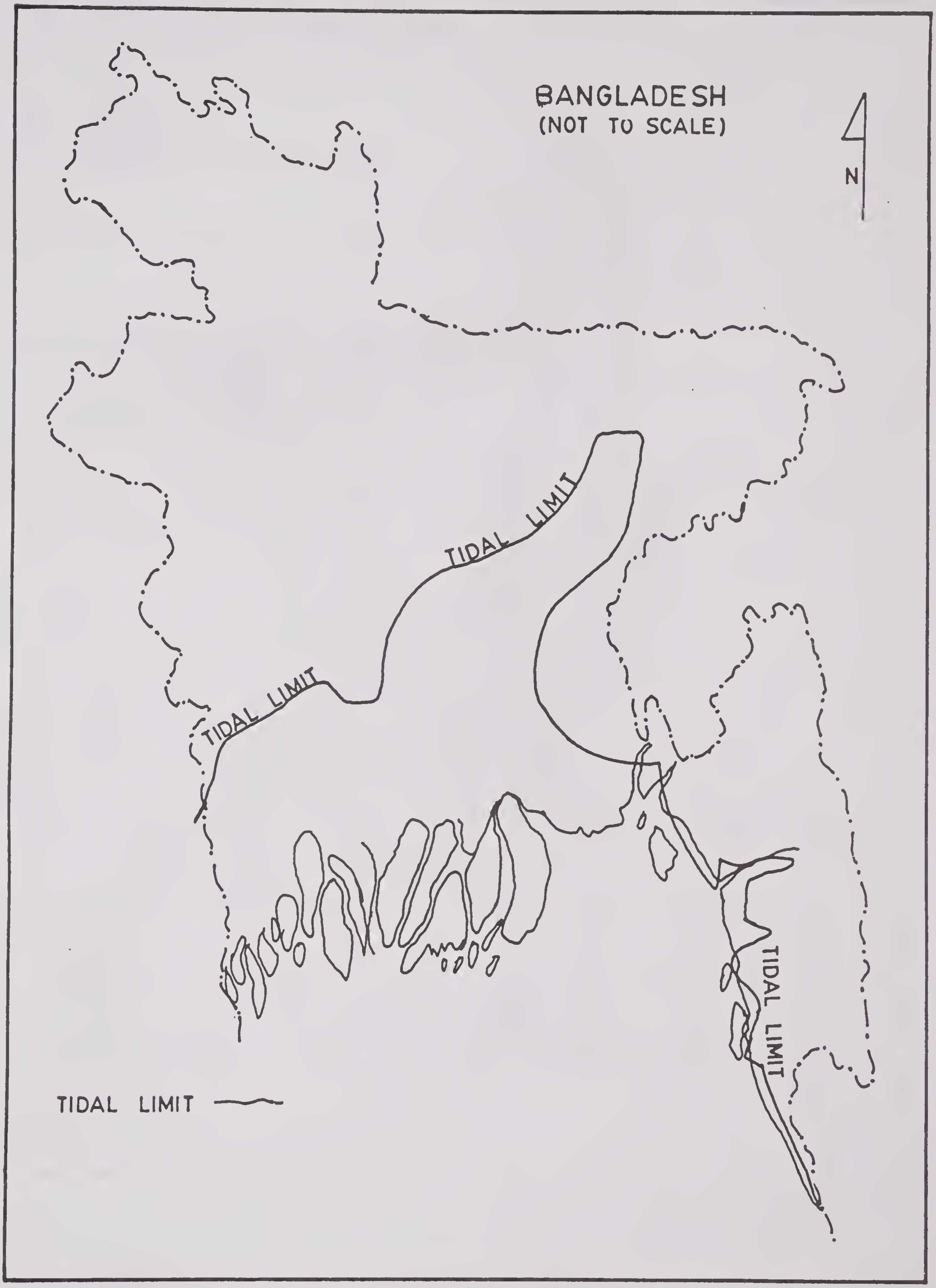
Any assessment of vulnerability should reflect a nation's capability to cope with the consequences of the effects of climate change. It should cover (1) physical changes and responses of the natural system to such climate changes; (2) the impacts of such changes on the socioeconomic conditions and ecological system, with emphasis on the sustainability for development; and (3) the capability of a society to respond to such impacts by taking mitigative or remedial measures.

The following possible effects of climate change have been considered in this study:

- Sea level rise
- Change in river discharge
- Change in intensity of precipitation
- Change in temperature/evaporation
- Cyclone frequency

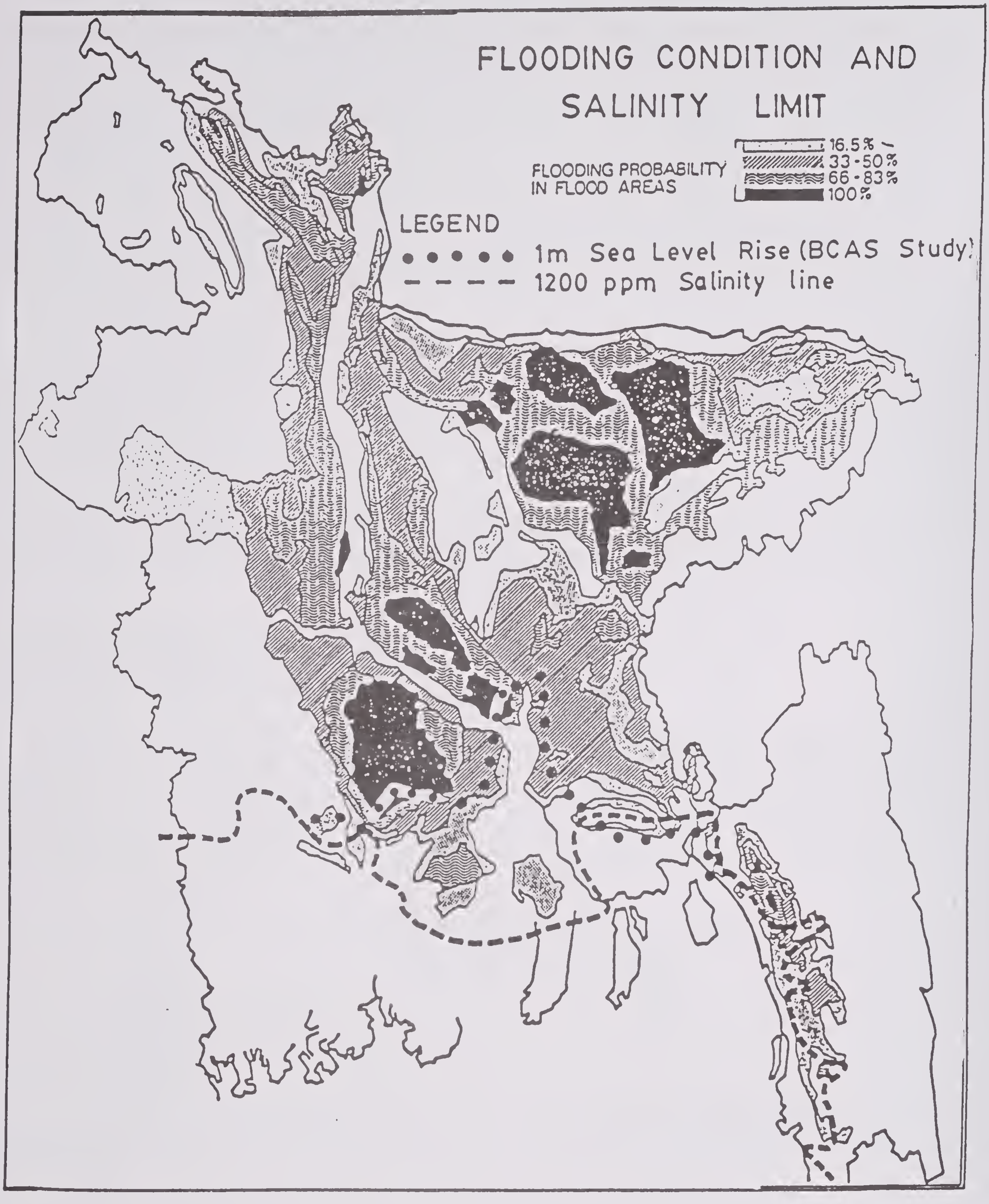
Therefore, for the purpose of this study the whole of Bangladesh has been taken as the study area (Figure 4).

FIGURE 2. TIDAL LIMIT



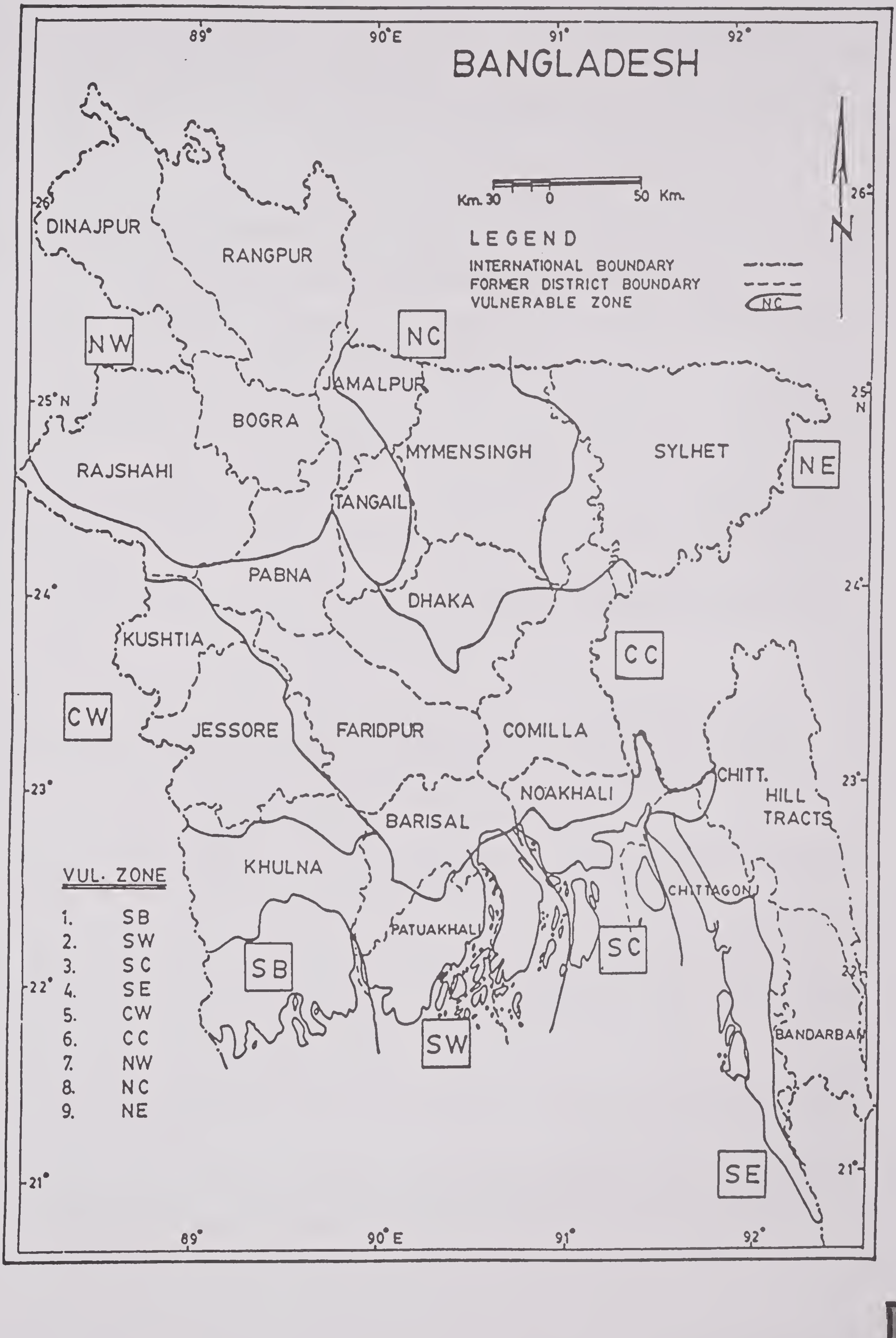
The tidal influence goes practically two-thirds up the country from the coast.

FIGURE 3. FLOODING CONDITION AND SALINITY LIMIT


FLOODING CONDITION AND SALINITY LIMIT
FLOODING PROBABILITY IN FLOOD AREAS
16.5% ~
33-50%
66-83%
100%
LEGEND
1m Sea Level Rise (BCAS Study)
1200 ppm Salinity line

Salt water from the coastal waters is steadily entering Bangladesh's ground water. The predicted 1-meter rise in sea level should exacerbate these conditions.

FIGURE 4. VULNERABLE ZONES



IMPACTS OF SEA LEVEL RISE

Table 1 shows the possible impacts of global climate change on Bangladesh. The relationship between possible physical impacts due to sea level rise and other climate changes on social, economic, and environmental parameters in Bangladesh are shown in Table 2. Due to shortage of time and lack of data and information, it is not possible to quantify the changes. Table 3 shows the physical characteristics and vulnerability to climate change.

TABLE 1. POSSIBLE IMPACTS OF CLIMATE CHANGE ON BANGLADESH

Effect of Climate Change Causing Possible Physical Changes

Possible Physical Changes	*Sea Level Rise*	*River Discharges*		*Precipitation*		*Temp./Evap.*	*Cyclone*
		Min.	Max.	Min.	Max.		
Inundations	x		x		x		
Flash Floods			x*				
Strom Surges	x						x
Droughts		x		x		x	
Salinity Instrusion	x	x		x		x	x
River Dynamics	x		x				
Coastal Dynamics	x						

x: Likely to be affected.
* Maximum discharge will cause flash flood.
** Erosion and/or accretion.

TABLE 2. POSSIBLE EFFECTS OF CLIMATE CHANGE ON SOCIAL, ECONOMIC, AND ENVIRONMENTAL CONDITIONS IN BANGLADESH

Environmental, Social & Economic Impacts

Physical Changes	*Agriculture*	*Industry*	*Infrastructure*	*Fishery*	*Biota*	*Human Health*	*Social Welfare*	*Population*
Inundations	x	x	x	x	x	x	x	x
Flash Floods	x	L	L	L				x
Storm Surges	x	L	x			x	x	x
Droughts	x	x		x	x		x	x
Salinity Intrusion	x			x	x	x		x
River Morphology			x		x			x
Coastal Morphology					x			x

x : Impact.
L : Local impact.

TABLE 3. NINE ZONES VULNERABLE TO CLIMATE CHANGE

Sl. No.	Zone	Code	Characteristics	Vulnerability to
01	Sunderbans	SB	* Coastal Zone * Mostly mangrove forest	* Inundation * Salinity intrusion
02	South West	SW	* Ganges tidal floodplain * Agricultural polders * Extensive shrimp farming * Coastal port and city (Khulna)	* Inundation * Salinity intrusion * Storm surges
03	South Central	SC	* Offshore islands * Meghna estuarine floodplains * Morphologically active rivers and coast * Major capture fisheries * Some large embankment schemes	* Flooding * Salinity intrusion * Coastal dynamics
04	South East	SE	* Coastal area * Mud flats and sandy beaches * Major port city (Chittagong)	* Flooding * Storm surges
05	Central West	CW	* Middle and higher Ganges floodplains	* Drainage congestion * Droughts in dry season
06	Central Central	CC	* Ganges, Meghna and Brahmaputra floodplains * River bank erosion * Major city and industries	* Flooding * Drainage congestion
07	North West	NW	* Himalayan piedmont * Relatively dry zone	* Flooding * Drought in dry season
08	North Central	NC	* Relatively high land * Modhupur Forest tract	* Drainage congestion * Drought in dry season
09	North East	NE	* Middle and higher floodplains of Meghna * Major inland wetlands	* Flooding * Drainage congestion

Two sets of boundary condition scenarios have been considered for this study:

Scenario I: For the year 2100, three possible boundary conditions are given in Table 4.

- "Average" assumes average changes.
- "Min. Max." assumes a minimal sea level rise of 0.3 meter and high levels of other climate changes.
- "Max. Max." assumes a maximum sea level rise of 1.0 meter and high levels of other climate changes. This boundary condition will establish for which set of parameters Bangladesh is most vulnerable.

TABLE 4. PROPOSED SCENARIOS FOR BOUNDARY CONDITIONS FOR THE YEAR 2100

Scenarios	SLR	Inundation	Drought	Flash Floods	Cyclone
Average	0.30 m	Average	Average	Average	Average
Min./Max.	0.30 m	High	High	High	High
Max./Max.	1.0 m	High	High	High	High

Scenario II: For the year 2030, Table 5 shows three possible situations that could be considered:

- The "Actual" sea level rise conditions.
- A "Future Max." condition, which assumes full implementation of flood and cyclone protection infrastructure works.
- A "Future Min." condition, which assumes another approach to the flood problem in Bangladesh.

The objective is to examine how vulnerable the country is to impacts of climate change under actual conditions and to identify which scenario of development makes the country more or less vulnerable. Nine possible scenarios could be considered, as given in Table 5.

TABLE 5. PROPOSED SCENARIOS TO BE INVESTIGATED FOR THE YEAR 2030

Scenarios	Actual SLR	Future Min. 0.3 m	Future Max. 0.3 m
Average	X		
Min. Max.	X	X	
Max. Max.	X	X	X

There have been a number of studies of the specific effect of an inundation of the coastal areas to different heights, usually 1 meter or less (Broadus et al., 1986; Huq and Ali, 1990; Mahtab, 1989; and Rahman, 1991). However, as the effects of climate change and even sea level rise in Bangladesh are unlikely to be confined to the coastal zone alone, this study has divided the country into nine separate vulnerable zones (Figure 4) whose characteristics are shown in Table 3. These have been done on the basis of agro-ecological, physiographic, flooding, drought, tidal flooding, and climate parameters.

The relative distribution of different environmental, social, and economic parameters existing within each zone have been computed from district-wise statistics of the Government of Bangladesh (Bureau of Statistics). Some examples are given in Table 6 (flood depth), Table 7 (coastal embankment), Table 8 (irrigated and rain-fed rice), Table 9 (infrastructure), Table 10 (land ownership), and Table 11 (population density and access to safe drinking water).

The likely impacts of a 0.3- and a 1.0-meter sea level rise on these as well as other parameters are being assessed. One example, given in Table 12, is the impact of sea level rise on agricultural production based on the likely inundation, as well as backwater flooding effects. It is quite clear from the studies that have been carried out so far that the effects of sea level rise and other climate change parameters are quite likely to be extremely severe on the people, their productive base and livelihoods, and natural ecosystems.

TABLE 6. AREA UNDER DIFFERENT FLOOD DEPTHS (20-YEAR FLOOD FREQUENCY)

Zone	Area (km^2)	Non-Flood F0 (km^2)	Shallow Flood F1 (km^2)	Medium Flood F2 (km^2)	Deep Flood F3 (km^2)	Very Deep Flood F4 (km^2)	Flood Protected Area (km^2)	Area occupied by Sundarban/Lower Meghna & Sea where flood depths were not determined (km^2)
NW	30,853	9,640	4,478	7,841	6,553	1,190	1,151	
NC	13,366	2,762	2,50	4,342	2,688	764	60	
NE	14,553	2,334	1,028	954	4,126	5,661	450	
CW	10,1624	5,037	2,009	2,358	794	-	426	
CC	24,466	932	2,110	8,174	11,145	815	863	427
SB	5,505	-	-	-	-	-	-	5,505
SW	13,041	123	208	5,639	830	-	4,682	1,559
SC	3,259	834	330	388	-	-	1,707	
SE	4,414	1,434	467	526	-	-	1,987	
Total	**12,0081**	**23,096**	**13,380**	**30,222**	**26,136**	**8,430**	**11,362**	

F_0: 0.0m < Flood depth ≤ 0.3 m.
F_1: 0.3m < Flood depth ≤ 0.9 m.
F_2: 0.9m < Flood depth ≤ 1.8 m.
F_3: 1.8m < Flood depth ≤ 3.6 m.
F_4: 3.6m < Flood depth.
Source: MPO.

TABLE 7. COASTAL EMBANKMENTS AND STRUCTURES IN VULNERABLE ZONES

Vulnerable Zones	Embankment (Km)	Structure (Nos.)
CW	153	30
SW	2,819	653
SE	787	256
SC	277	100
Total	**4,037**	**1,039**

Source: Bangladesh Water Development Board.

TABLE 8. RICE PRODUCTION IN DIFFERENT VULNERABLE ZONES (1989-90)

Vulnerable Zones	Irrigated Area (Ha)	Rice Production (MT) *Irrigated*	Rice Production (MT) *Rain-fed*
NW	1,040,000	2,158,000	3,393,000
NC	422,000	1,029,000	1,199,000
NE	284,000	682,000	959,000
CW	315,000	628,000	784,000
CC	600,000	1,371,000	2,322,000
SB	23,000	49,000	307,000
SW	67,000	428,000	1,140,000
SC	45,000	812,000	270,000
SE	88,000	225,000	336,000

Source: *Bangladesh Statistical Yearbook*, 1990.

TABLE 9. INFRASTRUCTURE WITHIN VULNERABLE ZONES (1989)

Vulnerable Zones	**Infrastructure**	
	Roads	*Bridges*
NW	2,098	16,562
NC	681	9,167
NE	853	0
CW	775	2,099
CC	1,529	12,262
SB	174	7,871
SW	331	7,521
SC	245	1,688
SE	334	19,482

Source: *Bangladesh Statistical Yearbook*, 1990.

TABLE 10. LAND OWNERSHIP PATTERNS IN THE VULNERABLE ZONES

Vulnerable Zones	**Land Ownership (%)**			
	Landless (Less than 1 acre)	*Small Farmer*	*Mid-Size Farmer*	*Large Farmer*
NW	56.37	33.46	5.50	4.67
NC	59.53	33.09	4.22	3.13
NE	55.36	33.62	4.07	3.52
CW	52.47	35.38	6.47	5.67
CC	56.32	33.46	5.50	4.67
SB	55.20	34.28	5.29	5.23
SW	55.08	35.88	4.68	4.23
SC	69.38	26.72	2.16	1.68
SE	72.76	23.62	2.02	1.53

Source: Bangladesh Agricultural Census 1983–84.

TABLE 11. ACCESS TO SAFE DRINKING WATER IN VULNERABLE ZONES (1990)

Vulnerable Zones	**Population (millions)**			**Population Density (per sq.km.)**	**Access to Safe Drinking Water (%)**
	Total	*Urban*	*Rural*		
NW	25.9	1.7	24.2	631	4.79
NC	14.5	3.5	11.0	539	5.84
NE	8.6	0.3	8.3	276	7.52
CW	7.7	0.6	7.1	518	4.37
CC	28	5.0	23.1	376	5.14
SB	2.3	0.4	1.9	229	4.74
SW	6.9	0.5	6.4	384	3.35
SC	3.4	0.2	3.2	328	4.77
SE	4.2	0.9	3.3	610	5.08

Source: *Bangladesh Statistical Yearbook*, 1991.

TABLE 12. POTENTIAL REVENUE AND CROP LOSSES FROM SEA LEVEL RISE

Vulnerable Zones	**Total Revenue (U.S. $)**			**Loss (%)**	
	Initial Situation	*0.3-m SLR*	*1.0-m SLR*	*Initial Situation 0.3-m SLR*	*Initial Situation 1.0-m SLR*
NW	$241,760	$237,129	$226,323	- 1.92	- 6.39
NC	122,582	117,174	104,556	- 4.41	- 14.70
NE	271,034	259,960	240,173	- 4.08	- 11.39
CW	505,394	492,692	463,052	- 2.52	- 8.38
CC	86,683	86,212	85,117	- 0.54	- 1.81
SB	NA	NA	NA	NA	NA
SW	166,760	126,423	98,636	-24.19	- 40.85
SC	32,660	25,551	21,158	-21.76	- 35.22
SE	42,661	30,714	21,894	-28.00	- 48.68
Total	**$1,469,534**	**$1,375,852**	**$1,260,909**	**- 6.37**	**-14.20**

Source: Based on Revenue Analysis, 1992.
NA: Not applicable.

RESPONSES TO SEA LEVEL RISE

The range of responses available to the people of Bangladesh to the likely impacts of sea level rise and climate change appear to be quite limited. They are discussed in terms of the three options: retreat, accommodation, and protection.

RETREAT

Considering the already highly dense population of the country and the likely increase in population, there are hardly any areas for people to retreat to within the boundaries of Bangladesh. Therefore, there will be increasing pressures for people to emigrate from the country, either to neighboring India or elsewhere, as is already happening. Within the country, there is also a tendency for people who lose their land and livelihoods to move into the more vulnerable zones, such as the newly accreted coastal lands and thus increase, rather than decrease, their vulnerability.

ACCOMMODATION

One major way of accommodating to sea level rise in the western zones would be to increase dry-season water flows though the Ganges River from upstream of Bangladesh. This would counteract the effects of saltwater intrusion and drought, which make the western zones particularly vulnerable during the dry season. However, this would require the cooperation of the upper riparian countries, India and Nepal.

A means of allowing controlled flooding of the major floodplains may prevent land subsidence and may allow the land to remain above the sea level.

PROTECTION

Protection against sea level rise may not be possible for many coastal areas, particularly the mangrove forests of the Sunderbans, which are already being threatened by saltwater intrusion and tidal siltation. This is equally true for large areas of the floodplain, which cannot be effectively protected at all.

Therefore, protection is only an option for ports and cities with high concentrations of capital and infrastructure. The same would be the case for the poldered agriculture and aquaculture areas along the coast. This would entail raising the existing embankments as well as constructing new embankments and sea walls in places. Such embankments would also offer some protection against cyclones and storm surges.

ECONOMIC, ENVIRONMENTAL, AND OTHER IMPLICATIONS OF THE RESPONSE STRATEGIES

ECONOMIC ISSUES

The different response strategies have not been evaluated sufficiently to estimate their costs at this stage. However, some estimates from other sources may be indicative. For example, a proposal for building embankments along the major rivers of Bangladesh for flood protection was estimated to cost about $10 billion (U.S.) in 1989. Although this scheme of building massive embankments is no longer under consideration, it gives an idea of the approximate costs involved. The loss of biodiversity of rich coastal ecosystems, such as the mangrove forests of the Sunderbans, can hardly be estimated in dollar terms.

POLITICAL ISSUES

The first step in assessing and evaluating suitable response strategies would require the acceptance of the need for a vulnerability assessment and response strategy by the highest levels within the country, which has yet to be achieved. Once this is done, different agencies that may need to be involved can be coordinated.

INTEGRATION OF PLANNING ACTIVITIES

It would also be necessary to integrate these studies with other ongoing developments, such as the Flood Action Plan.

Following the disastrous floods of 1987 and 1988, the Government of Bangladesh conducted comprehensive studies of flood policy. In June 1989, the Government of Bangladesh requested the World Bank to develop and coordinate a 5-year Flood Action Plan (1990–95), drawing on these studies, as the first step in the government's long-term Flood Control Program.

The Flood Action Plan aims at identifying, planning, designing, and constructing high-priority projects that are technically, economically, environmentally, and socially feasible. It consists of 11 components and 16 supporting activities. The Action Plan will be undertaken in parallel with agricultural and rural development programs and a program of new structural measure, including flood warning and flood preparedness. Almost all the plan's actions have been initiated and are in various stages of study and completion.

DEVELOPMENT OF INSTITUTIONAL CAPABILITIES

Once the need is accepted at the highest political levels, national institutional capabilities must be developed to study and analyze the issues and problems and to frame recommendations for strategies to be adopted. This will necessitate considerably strengthening the national capacity for data gathering and analysis as well as for interinstitutional cooperation at the ground level in each of the affected zones.

EXTERNAL ASSISTANCE

For a poor, developing country like Bangladesh where all its economic resources are used for immediate development needs, it is practically impossible to spare resources for longer-term planning concerns, however compelling. Therefore, if Bangladesh is to respond to sea level rise and climate change, it will require substantial external financial and technical assistance. A first step in such assistance should be to provide the national capability to prepare a thorough vulnerability assessment and appropriate response strategies as soon as possible.

CONCLUSIONS AND RECOMMENDATIONS

Although Bangladesh is well known both nationally and internationally as the country with the largest population vulnerable to sea level rise, there has been almost no attempt nationally and only piecemeal attempts internationally to assess the likely real impacts to the country and to formulate a viable response strategy. It is high time that this be done without further delay.

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THE IMPACTS OF SEA LEVEL RISE ON CHINA'S COASTAL AREAS

Xu Qiwang, Lu Chunhua, Zhang Yushu, and Niu Bin
National Marine Data and Information Service
People's Republic of China

INTRODUCTION

The sea level rise caused by global climate warming and its impacts on the natural environments, ecosystems, and social economies of coastal areas have been the subjects of concern throughout the world. China has a long, densely populated coastline, with rich resources and a developed economy. Several of China's rivers empty into the sea, such as the Changjiang, Huanghe, Zhujiang, Liaohe, and Haihe Rivers (Figure 1). These rivers carry large amounts of silt into the sea every year, resulting in many deltaic alluvial plains that occupy a large proportion of China's coastline. The rich alluvial plains of the Huanghe, Changjiang, and Zhujiang Deltas are rarely found elsewhere in the world.

TRENDS IN CHINA'S SEA LEVEL RISE

Since the 1980's, China has attached great importance to the study of changing sea level. Numerous marine scientists have made a detailed survey and analysis of the change of China's coastal sea level. Most scientists believe that rising sea level along China's coast is closely associated with global sea level rise. Furthermore, subsidence in a few coastal cities caused by overexploitation of ground water has accelerated the rate of relative sea level rise.

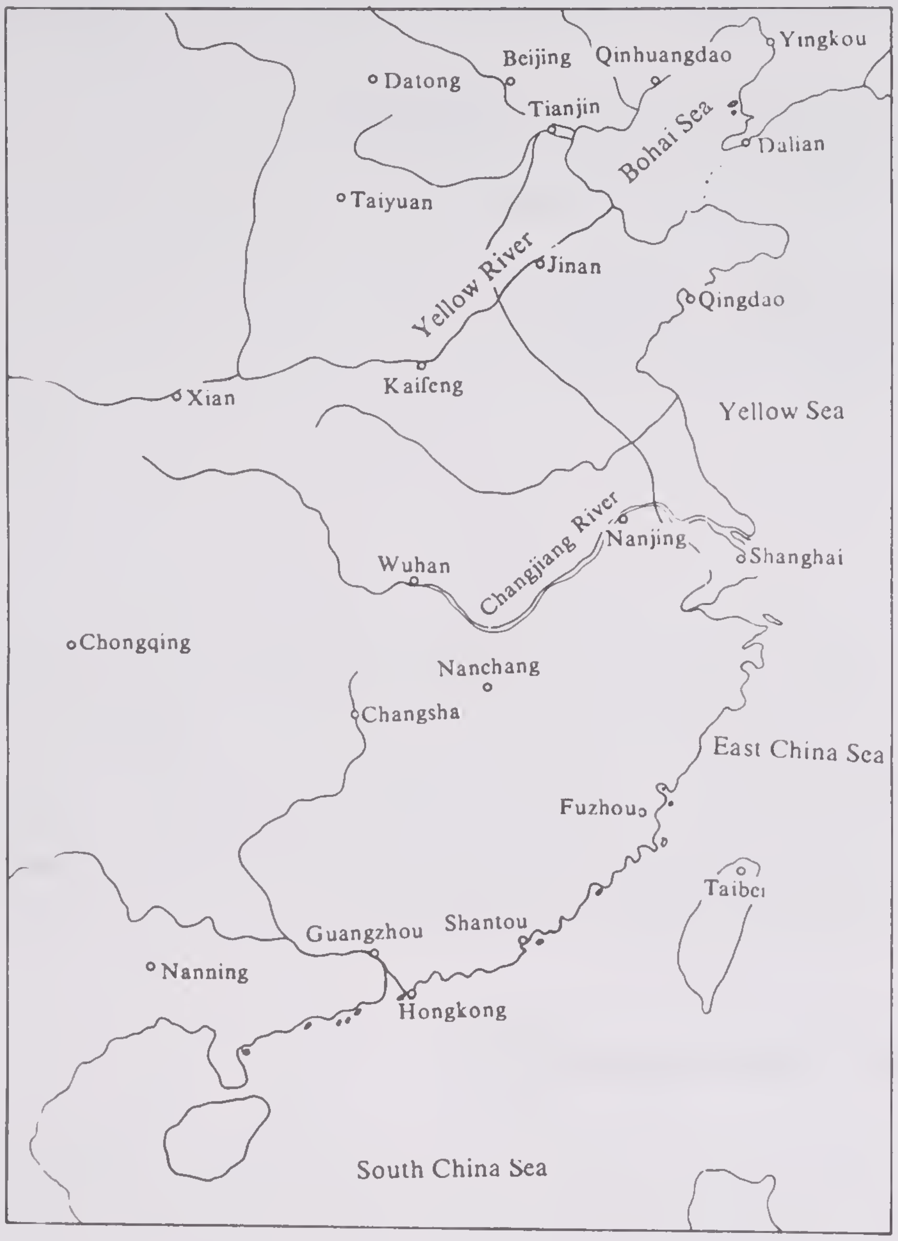
Table 1 lists the research findings of some scholars on sea level rise along China's coast. It shows that they agree on the general trend in the past few decades or in the past century—i.e., the sea is rising at a rate of 1.4–3.0 mm/year. However, the change in sea level is different in different places, and in some sections, the level is falling.

Although at present it is difficult to accurately predict future sea level changes, it is necessary to make a rough estimate of its potential impacts with a view to develop potential responses to likely impacts. Therefore, this paper assumes a future rise of 0.5–1.5 meters.

IMPACTS OF SEA LEVEL RISE ON CHINA'S COASTAL AREAS

China's coastal areas have always been economically developed and densely populated. Especially in the past decade, under the guidance of the policy of reform and opening to the outside world, China's coastal areas have seen particularly rapid economic development and have become the first zone with a developed social economy.

FIGURE 1. CHINA'S COASTAL AREAS



According to statistics, China's 11 coastal provinces and municipalities (not including Taiwan and the Hong Kong and Aumen regions) occupy only 13.2 percent of the national total land area, while their gross output value of industry and agriculture makes up over half of the national total. The total area of the coastal zone covers 28.5 x 10^4km^2, and the area of the land and the tidal flat of the coastal zone cover 12.8 x 10^4km^2. The long and narrow coastal zone is inhabited by 12.9 percent of the national total population, which accounts for 32 percent of the total population in the coastal provinces (municipalities). Thus, the population density of the coastal zone is 4.4 times that of the national average. The statistics indicate that the gross output value of industry and agriculture of China's coastal zone, accounts for 24.5 percent of the national total and 45 percent of the eastern coastal provinces (municipalities).

But the natural disasters in the coastal area, especially the frequent marine natural disasters, have significantly affected the development of China's coastal economy. Between 1980 and 1989, natural disasters in the coastal area amounted to an estimated loss of 870 million yuan (RMB) every year on the average. In 1989 alone, the direct economic losses caused by various marine natural calamities—mainly the storm surges occurring in the coastal areas—amounted to 6 billion yuan (RMB). The future sea level rise will exacerbate these losses, increasing erosion, flooding, storm surges, and saltwater intrusion.

TABLE 1. CHANGES IN CHINA'S SEA LEVEL

Author	Study Section	Rate of Rise (mm/year)	Methodology or Data Used
Zheng Wenzhen et al. (1989)	China's Coast	1.4	48 tidal stations (Centenary mean)
	Tianjin Coast	2.1	
	Shandong Coast	-0.3	
	Jiangsu and Shanghai Coast	2.0	
	Guangdong Coast	2.2	
You Fanghu et al. (1981)	China's Eastern Coast	2.5	8 tidal stations
Zhao Mingcai et al. (1986)	China's Coast	2.3	10-year periodic method
Wang Zhihao (1986)	China's Coast	3.0	13 tidal stations
Yu Mugeng (1989)	China's Coast	2.6	10-year and 11-year periodic methods
Yu Daoyong (1986)	China's Coast	2.1	16 tidal stations

COASTAL EROSION AND INUNDATION

Over 95 percent of China's coastal resources lie in the tidal zone of the continental coastline. The salt pan occupies over 3,700 km^2, and the cultivated tidal flat occupies more than 2,600 km^2. If sea level rise by 0.5–1.5 meters, over half of the tidal flat will be flooded with salt water. Although China has constructed protective structures, such as sea walls, in some big coastal cities, a 0.5–1.5 meter rise would flow over a great part of the existing sea walls.

Several sections of China's long coastline have been eroded. The silt and mud coast and the gravel coast are particularly vulnerable to serious erosion and shoreline retreat. Extending over 4,000 km, the muddy coast in China is mainly distributed over the sections of the Bohai Gulf, Laizhou Bay, northern Jiangsu, Changjiang River mouth, harbors and bays in Zhejiang and Fujian provinces, and the Zhujiang River mouth. Part of the Tianjin coast is eroded, and part of the coast along Hangzhou Bay is losing dozens of meters of land every year. The erosion rate is even worse along the coast of northern Jiangsu, and nearly half of Shanghai's 450-km coastline is eroded. A 0.5- to1.5-meter rise would surely increase coastal erosion.

EXACERBATION OF STORM SURGE HAZARDS

Storm surge hazards are frequent and serious along China's coast. Between 1951 and 1990, there were over 250 typhoon storm surges with a maximum setup of over 1 meter, and over 40 of those had a maximum setup of over 2 meters. These storm surges caused nearly 40 exceptionally serious tidal calamities. Similarly, between 1950 and 1990, in the Laizhou Bay and the Bohai Gulf, there were more than 520 temperate storm surges with a maximum setup of over 1 meter, of which nearly 60 had a maximum setup exceeding 2 meters. These storm surges resulted in eight major tidal disasters. The big coastal cities and open ports of Tianjin, Shanghai, Ningbo, Beilun Port, Wenzhou, Mawei Port in Fuzhou, Shandou, Guangzhou, Zhanjiang, and Haikou are all located in areas where serious storm surges often occur. A future rise in sea level will increase the number of disasters from storm surges.

TABLE 2. STORM SURGES AND TIDAL
CALAMITIES ALONG CHINA'S COAST (1951–1990)

Type	Number of Storm Surge Setup			Number of Tidal Calamities
	> 1 m	*> 2 m*	*> 3 m*	
Typhoon Storm Surge	253	45	8	91
Temperate Storm Surge	520	57	4	70

The Zhujiang Delta, the Yellow River Delta, the Changjiang Delta, and the Bohai Gulf are major economic centers of China. Some of these low-lying areas are normally about 1.5–4.0 meters above sea level. With a 0.5- to 5-meter rise in sea level, storm surges would partly or completely flood farmland, villages, towns, and coastal installations and harbors. Although some big cities, such Shanghai and Guangzhou, are essentially protected by sea walls, they may still be flooded under those conditions. With a rise in sea level, the storm surge tidal level may be raised by a large margin. The original storm surge tidal levels with return periods of 1,000 years and 100 years may have new return periods of 100 years and 50 years, respectively. Therefore, the original sea walls and flood-control walls will inevitably be unable to protect against storm surges.

Rough calculations indicate that, if sea level rises by 0.5, 1.0, and 1.5 meters, in cases of the highest water level on record and the multiyear mean spring high-water level, these areas will be in great part subject to tidal calamities (Tables 3 and 4). For example, with a 1.0-meter rise, 32,500 km^2 may be flooded in the case of spring high-water level, and 81,400 km in the case of the highest water level on record. Agricultural production will be significantly diminished, and it may take several years for the land to recover from the salinization caused by the salt water.

AGGRAVATION OF SALTWATER INTRUSION

Saltwater intrusion has been a serious problem in China in recent years. The main causes are the overexploitation of ground water due to lack of surface-water resources and the successive years of drought that have lowered the level of ground water. These causes have resulted in a negative-value funnel area, which allows the salt water to enter the ground water. For example, in the cities of Laizhou and Longkou of Shandong province, over 70 and 80 km^2, respectively, are contaminated by salt water. Sea level rise also increases saltwater intrusion into the river mouth and moves the coastline inland, pushing forward the boundary between salt water and fresh water and increasing the chloride content in the water of the river mouth. And during the dry season, the salt water will penetrate deeper and farther into the river. If sea level should rises by 0.5–1.5 meters, the 0.5 percent isohalsine at the Changjiang River mouth will migrate upstream for dozens of kilometers, which will directly affect the industrial and agricultural production and potable water supply for inhabitants in Shanghai and other areas.

Sea level rise will also significantly affect China's social economy. The long-term deterioration of the living environment is bound to force the people to move to other places. For example, if the coastal population of Shanghai and Tianjin moves inland, it will cost dozens of billions of yuan (RMB), not to mention the losses incurred in the destruction of the existing economic facilities that will have to be relocated or possibly abandoned.

TABLE 3. AREAS AT RISK OF TIDAL CALAMITIES FROM FUTURE SEA LEVEL RISE (KM^2)
(Calculated in Case of the Multiyear Mean Spring High Water)

SEA LEVEL RISE	REGION			TOTAL
	Zhujiang Mouth Area	Changjiang Mouth Area	Littoral Area of Bohai	
0.5 m	300	17,200	1,300	18,800
1.0 m	900	25,800	5,800	32,500
1.5 m	1,500	34,400	10,300	46,200

TABLE 4. AREAS AT RISK OF TIDAL CALAMITIES FROM FUTURE SEA LEVEL RISE (KM^2)
(Calculated in Case of the Highest High Water on Record)

SEA LEVEL RISE	REGION			TOTAL
	Zhujiang Mouth Area	Changjiang Mouth Area	Littoral Area of Bohai	
0.5 m	1,600	49,300	19,200	70,100
1.0 m	1,900	56,900	22,600	81,400
1.5 m	2,100	62,100	26,000	90,200

COUNTERMEASURES AND RECOMMENDATIONS FOR RESPONDING TO SEA LEVEL RISE

There are two strategies of responding to future sea level rise: active attack and active defenses. Active attack means to settle the problem once and for all—i.e., to take countermeasures in light of the main cause of the sea level rise, which is society's use of large amounts of fossil fuels. According to this model, the fundamental way of preventing sea level rise would be to control air pollution and prevent global warming. However, due to man's dependence on fossil fuels, it seems impossible now to effectively control CO^2 emissions globally. Global warming cannot be checked at least in the near term. Therefore, the best option appears to be active defense.

STRENGTHENING CAPABILITIES FOR MONITORING AND PREDICTING SEA LEVEL RISE

Tidal station networks have been set up in some major coastal countries, and some tidal stations have made continuous observations for as many as 100 years, accumulating a large volume of valuable data. But as a global monitoring system, the gathering has been inadequate. The distribution of observation stations is not quite rational, the technical facilities are not uniform, and the time sequences of the observations for most tidal stations are relatively short. Consequently, a global sea level observation system has been set up, and several countries are working together to steadily improve and perfect the system.

Most of the tidal stations in China have been developed since the founding of the People's Republic of China and thus have a short history. To enhance China's ability to conduct research on and to predict sea level rise, the management and construction of the tidal stations in the country must be improved, a unified tidal station network must be set up at the national level, and unified standards must be developed. It will also be necessary to upgrade the instruments and equipment and to raise the level of automation and the quality of observation. A modernized system can serve the current needs for economic construction, national defense, and ocean development and can provide reliable data for sea level research and prediction. In the meantime, efforts must be made to actively collect and fully make use of the data available both at home and abroad, to conduct research on the causes of and trends in sea level rise in China and throughout the world, and to predict changes in sea level in some important areas of China in the coming 10–20 years.

INTENSIFYING PRECAUTIONS AGAINST NATURAL DISASTERS

In view of the possible hazards that may result from sea level rise, it is essential to take effective precautions as early as possible. Potential responses may fall into three categories: accommodation, defense, and control.

ACCOMMODATION

In planning construction in commercial and residential areas along the coast, it is necessary to consider the consequences of the future sea level rise. Different planning options should be considered, based on predictions of future sea level rise and the coastal topography:

- Areas where the coast has been seriously eroded should not be developed. In areas vulnerable to sea level rise that are slated for development but that have not yet begun to be developed or are only in the initial stages of development, all development activities should be terminated.

- In regions where the storm surge calamities are now frequent and serious, residential areas that are not densely populated could be moved inland, while retaining the recreational value of the original beaches.

- To avert the damage from storm surges, it is essential to raise the design criteria of the coastal protection projects and the seaside structures. Designs of offices and production workshops should place the costly equipment above the predicted future sea level.

DEFENSE

Such protective structures as tidal barrages, flood-control dikes, and waterproof walls can effectively protect against rising tide and reduce coastal erosion. If these defense measures could be combined with enclosing the tidal flat and the mariculture projects to attain the dual purpose of development and protection, better synthetic results might be achieved. However, effective and economic protection measures must be based on accurate and reliable information on changes in sea level. And because defense engineering entails large investment, the areas protected must have significant value, such as major ports, national defense facilities, important historical relics, and environmental protection areas.

CONTROL

The overexploitation of ground water due to the development of coastal industries and the lack of water in the cities, and the exploitation of offshore oil have caused serious subsidence along China's coast. For example, between 1921 and 1956, the surface area of Shanghai city proper has subsided by 2.63 meters, with a maximum annual subsidence of 110 mm. During a storm surge in 1962, the tidal level off Shanghai's Huangpu Park rose to 4.76 meters. Because of subsidence, the flood-control wall was breached in 46 places, flooding half of the city proper. The city suffered an economic loss of 500 million yuan (RMB), and the flood-control wall had to be heightened after the flood. Similarly, the Xinggang area of Tianjin has experienced serious subsidence. As a result, the elevations of the harbor projects are lower than the design criteria, which has weakened the capability of the harbor structures to resist storm surges. In 1985 when attacked by two successive storm surges, the wharves in Xinggang were flooded, and most of the freight yards and storehouses were submerged.

Therefore, in developing strategies for protecting against the hazards of the sea level rise, it is necessary to control subsidence in the coastal areas, especially the port cities. Currently, the most direct approach to controlling subsidence is to control the exploitation of ground water or to fill the wells with water. This approach has proven to be effective in Shanghai and Tianjin.

With regard to saltwater intrusion, since this problem tends to be caused by drought and sea level rise, reservoirs may be built in the lower reaches of the river, and during the dry season water can be discharged to slow down the maximum current velocity of salt water invading along the river. Moreover, to ensure the adaptation of certain species to the salt water and their migration upstream, it is necessary to control the pollution of the water coming from the cities in the upper reaches of the river.

SURVEYING AND MAPPING IN COASTAL AREAS

These precautions against natural calamities cannot be practiced without understanding the topography of the coastal zone. Detailed topographic maps of the area are required, especially for the coastal cities, ports, and economic development zones with concentrated industries and dense populations. These maps provide basic data for developing projects, for protecting against natural calamities, and for planning the transfer and evacuation of populations. Although these maps are indispensable for planning responses to sea level rise, China does not have detailed topographic maps at present. The diagrams and tables in this paper, which assume a future sea level rise of 0.5–1.5 meters, are rather rough. Considering the long-term planning necessary to protect against natural calamities, it is essential to incorporate the surveying and mapping of the detailed topography of the coastal zone into the state plan as early as possible, so that the work can be staged out methodically step by step. Stress should be put on the topographic surveying and mapping of a few important coastal zones in the near future, and efforts should be made to strive for the completion of a set of detailed maps on China's major coastal zones by the end of the century, so as to provide an accurate and reliable basis for making decisions on protecting against coastal natural calamities.

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THE IMPACTS OF SEA LEVEL RISE IN THE YEAR 2100 ON BOHAI BAY, THE HUANGHE RIVER DELTA, AND LAIZHOU BAY

Liu Zhenxia, Xia Dongxing, Wang Delin,
Li Xuan, Wu Sangyun, and Li Fulin
First Institute of Oceanography
State Oceanic Administration
Qingdao, People's Republic of China

INTRODUCTION

The rise of sea level caused by the greenhouse effect and its impacts have become the hot point of research of many branches of science. Special research on the mechanics, speed, prediction, and response strategies of sea level rise have been carried out by the United ations Environment Programme (UNEP), SCOPE, the Intergovernmental Panel on Climate Change (IPCC), the World Meteorological Organization (WMO), the United States Environmental Protection Agency (EPA), and other international organizations, governmental departments, and scientists from various countries. Most of the research has shown that global mean sea level has been rising slowly in the past 100 years.

In August 1991, the IPCC asked China to provide two case studies on the effects of sea level rise in the next century. The State Oceanic Administration of the People's Republic of China chose Tianjin municipality in the coastal area to the west of Bohai Bay, the coastal area of Laizhou Bay, and the Huanghe (Yellow) River delta as the first batch of case studies. As the two areas adjoin, the two case studies are merged into one for the purpose of convenient description.

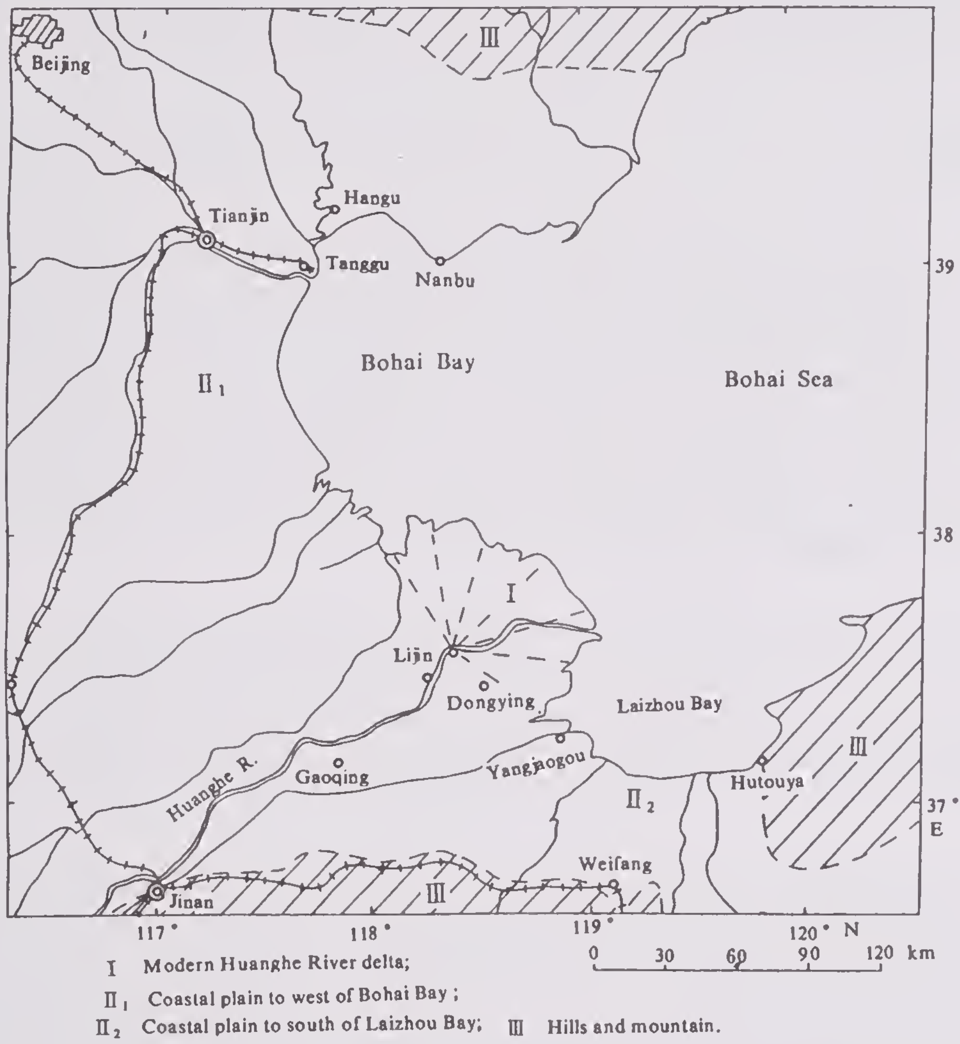
The study area is highly vulnerable to sea level rise. The coastline from Nanbu in Hebei province in the north to Longkou in Shandong province in the south is nearly 1,000 kilometers. By 2100, taking the local ground subsidence into account, over 10,000 km^2 will be lost if the global sea level is 0.3 meters higher than today, and 12,000 km^2 if it is 1.0 meter higher. Tianjin, the third largest city in China, will be inundated. The total economic loss will amount to $12 billion (U.S.). To protect against future sea level rise, we recommend the comprehensive approach of building sea walls, diverting the Huanghe River to settle its sediment loads, and raising the construction base.

NATURAL GEOGRAPHY OF THE STUDY AREA

The study area is located on the west and south coasts of the Bohai Sea (116° 30′–120° 00′E, 36° 50′–39° 50′N), extending from Nanbu in the north to Longkou in the south. The study area belongs to Hebei province, Tianjin municipality (the western coastal area of Bohai Bay) and Shandong province (the southern coastal area of Laizhou Bay and the Huanghe River delta), respectively.

The study area is mainly composed of plains consisting of alluvial-marine deposits and river deltas, except for the eroded plain to the east of Laizhou Bay. From north to south, the geomorphological units are: (1) the coastal plain to the west of the Bohai Bay, (2) the modern Huanghe River delta, and (3) the coastal plain to the south of Laizhou Bay (Figure 1). The ground of the study area is low, with a smoothly low-sloping gradient. The ground altitude of the west coastal plain of Bohai Bay varies from 0.5 to 3 meters, with a slope gradient of .01 to .02 percent; the ground altitude of the Huanghe River delta varies from 1.0 to 7.0 meters with a slope gradient of .01 to .02 percent; and the altitude of the bayhead plain of Laizhou Bay is lower than 5 meters, with a slope gradient of .01 to .03 percent, while the ground altitudes of the coastal plains on the west and east sides of Laizhou Bay are slightly larger (Table 1).

FIGURE 1. LOCATION OF THE STUDY AREA



In recent decades, the west coast of Bohai Bay has been seriously eroding, resulting in the inland migration of the natural coastline and the scouring away of the tidal flats. Tectonically, the study area is largely located in the second subsidence zone of the Neocathaysian Structural System, which has been subsiding since the beginning of the Cenozoic era. The Quaternary deposition alone in the coastal plain of Laizhou Bay and in the Huanghe River delta is 50 to 300 meters thick, and that in the coastal plain to the west of Bohai Bay varies from 350 to 600 meters. Since the upper Pleistocene (about 100 Ka B.P.), the study area has been flooded with salt water three times. In the Holocene epoch, rivers, lakes, and swamps have developed in this area.

The main rivers entering the sea in the study area are listed in Table 2. The Huanghe River is the largest, discharging about 1 billion tons of sediment each year (the annual sediment discharge of the Huanghe River has decreased slightly over the last 10 years). The total sediment discharge of all the other rivers in this area is less than 1 percent of that of the Huanghe River. In the stage all the other rivers in this area is less than 1 percent of that of the Huanghe River. In the stage from 3000 B.C. to 1128 A.D., the Huanghe River entered the sea at a place near Tianjin. Since 1855 A.D., the Huanghe River has been entering the sea via Lijin, Shandong province, and has built a vast delta system composed of both old and new deltas. The Huanghe River is famous for its high sediment load and relatively small amount of runoff; the sediment content of the river water is the highest in the world. The sea-reach channel of the Huanghe River frequently shifts from place to place, and has shifted on a large scale 10 times since 1855 A.D.. As a result, it has built the modern Huanghe River delta which stretches across 5,200 km^2, with its apex located at Ninghai. The spits at the mouth of active river channel silts seaward rapidly, with the maximum speed of 8 to 10 km/year, and the average rate of accretion of the Huanghe River delta is 21 km^2/year. While the abandoned delta lobes are subject to erosion, the erosional process is extremely intense in the early stage.

TABLE 1. GENERAL CHARACTERISTICS OF THE STUDY AREA (IN METERS)

Characteristics	**West Coast of Bohai Bay**	**Huanghe Delta**	**South Coast of Laizhou Bay**
Length of Coastline (km)	374	409	136
Ground Elevation (m)	0.5-3.0	1-7	< 5
Slope (%)	0.01-0.02	0.01-0.02	0.01-0.03
Q Thickness (m)	350-600	200-300	50-200
Mean Annual Temperature (C)	11.2	11.7-12.6	11.7-12.6
Mean Annual Rainfall (mm)	560-580	580-660	580-660
Mean Annual Evaporating Capacity (mm)	1,920-2,400	1,750-2,430	1,750-2,430
Tidal Range (m)	1.5-2.5	0.24-1.0	0.9-1.5
Soil	saline soil--salinized aquent--aquult		
Vegetation	halophyte community(Suaeda-Aeluropus-Pragmites)		
Coastal State	erosion	aggradation	stable

The climate in the study area belongs to the continental climate of the East Asia monsoon-type in the Warmer Temperate Zone: hot and rainy in summer and cold and dry in winter. Precipitation is low, and evaporation is relatively high—about three times higher than the precipitation.

Except for Nanbu at the north end of the study area, which has regular semi-diurnal tides, the tides at all the other places along the coasts of the study area are irregular semi-diurnal tides, with the tidal ranges varying from place to place. The waves in the study area are mainly wind waves, which are obviously controlled by monsoons. The directions in summer are mainly NE–

dominant waves are NE–NNE. Temperate-zone storm surges frequently occur in this area, especially along the south coast of Laizhou Bay.

TABLE 2. DISCHARGES OF THE MAIN RIVERS IN THE STUDY AREA

River	Time Interval	Mean Annual Sediment Discharge (10^4 T)	Mean Annual Discharge (10^8 m)
Jiyunhe	1978-1983	6.2	
New Chaobaihe	1973-1983	16.5	
Haihe	1974-1983	1.8	
New Yongdinghe	1973-1983	4.0	
New Zhangweihe	1973-1984	60.0	6.52
Majiahe	1956-1979	84.8	4.43
Tuhaihe	1956-1979	88.1	9.41
Huanghe	1950-1985	104,900	419
	1976-1985	83,000	338.5
Xiaoqinghe	1956-1979	34.7	12.3
Mihe	1956-1979	108	5.49
Weihe	1956-1979	342	9.68
North Jiaolaihe	1956-1979	9.6	4.82

Modern Sea Level Changes

Recent Changes in Sea Level

Statistical results from several hundred tidal gauging stations around the world show that the global mean sea level has risen 0.1–0.2 meters in the past 100 years, at an average rate of 1–2 mm/year (IPCC, 1990). The tendency of changes in mean sea level in China is the same as that of the global changes in mean sea level. According to *Reports of Sea Levels in China*, published by the China's State Oceanic Administration (1989, 1990), the sea levels along the coasts of mainland China have risen an average 14 cm in the past 100 years.

The rate of sea level rise in China in the past 100 years is close to that of global sea level rise. Estimates of the annual rate of sea level rise in China vary from 1.0 to 3.5 mm (Table 3). According to statistics from the 48 long-term tidal gauging stations of China, the average rate is 1.4 mm/year. Since the 1960's, the rates of sea level rise have increased by an average of 2.1 to 2.3 mm/year.

There are three tidal gauging stations in the study area. Data from the Tanggu station (1950–89) show the average rate of sea level rise to be 2.1 mm/year; at Longkou station (1961–89), the average rate is 0.3 mm/year; and at Yangjiaogou station (1972–88), 1.6 mm/year (Zheng Wenzhen, 1991). Thus, the rate of sea level rise in Bohai Bay is higher than in Laizhou Bay, and the rate in the west part of Laizhou Bay is higher than in the east part of the bay. These different rates might reflect different land movements. In general, the rises in sea level in the study area have kept pace with those of China and the world, being in the range of 0.3–2.1 mm/year.

TABLE 3. ESTIMATES OF SEA LEVEL CHANGES IN THE CHINA SEAS

Rate (mm/year)	Stations and Period	Sources
2.5	8 stations	Emery & You Fanghu (1981)
3.5	13 stations	Wang Zhihao (1986)
2.3+0.9	9 stations 1960-1980	Zhao Mingcai & Zhang Dachu (1986)
2.1	16 stations 1960-1980	Yu Daoyong (1986)
3.0	11 stations	Yang Huairen & Chen Xiqing (1987)
1.0	Changjiang Estuary 1922-1987	Chen Xiqing (1990)
2.5	Changjiang Estuary 1952-1987	Chen Xiqing (1990)
1.0-1.2	4 stations of Changjiang Estuary, last 20-35 years	Chen Zongyong et al. (1991)
1.4	48 stations	SOA (1989, 1990)

ESTIMATES OF FUTURE SEA LEVEL RISE

Because many uncertainties influence sea level rise, the predicted rises vary significantly. The estimate of sea level rise made before the 1980's were relatively large. In 1990, the IPCC estimated that sea level would rise three to six times faster than in the past 100 years (Figure 2). Under the "business as usual" scenario, global sea level will rise 0.31 to 1.10 meters by 2100 A.D., most likely by .66 meters. Even if society takes measures to reduce or to prevent the increase of greenhouse gas emissions by 2030 A.D, global sea level will still rise by .25 meters in the first 70 years of the next century because of the thermal inertia of the oceans and the continuing response of land ice to climate changes (IPCC, 1990).

THE EFFECT OF LAND SUBSIDENCE

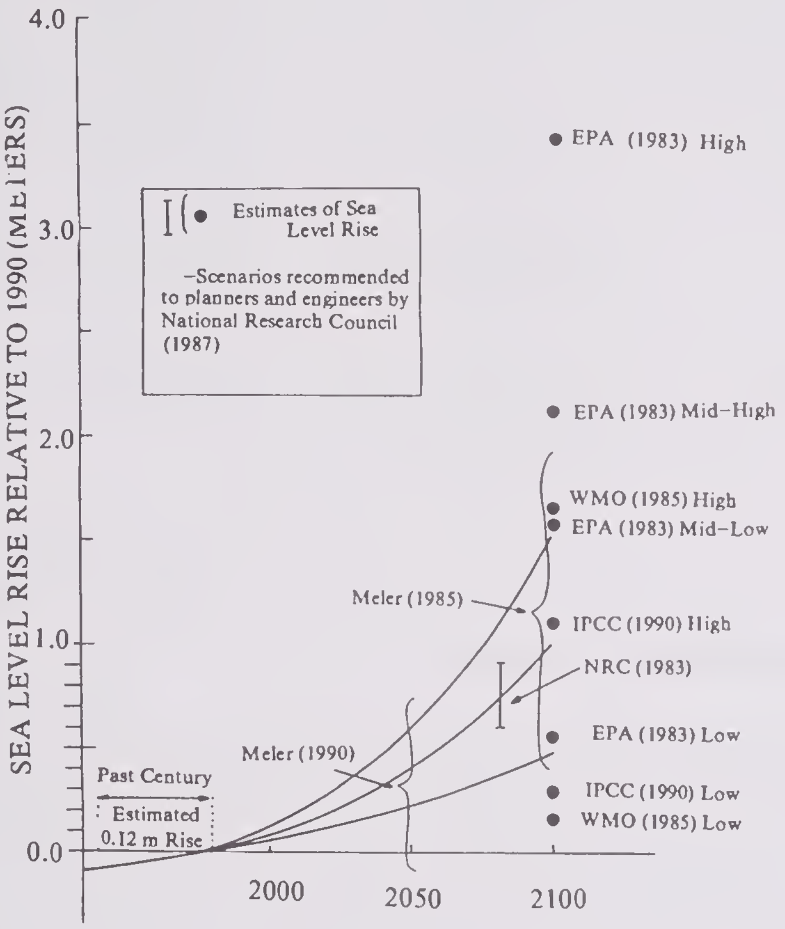
Tianjin municipality has experienced the most serious land subsidence in China. This subsidence is caused by three factors:

- *Tectonic subsidence.* Tianjin municipality is tectonically located in the Hebei-Shandong Depression Zone. Under the control of regional tectonics and the differential fault-block movement, the basement has been subsiding in the Tertiary and Quaternary periods at the rate of -3 to -4 mm/year.

- *The compaction of loose sediment layers.* Tianjin region was the old delta of the Huanghe River 1,000 years ago. At present, it is the alluvial plain of the Haihe River, which consists of five tributaries, with a loose sediment layer that is full of water and is very thick.

- *The exploitation of ground water.* In 1959, the benchmark of Tianjin was subsiding by -4 to -6 mm/year, mainly as a result of natural factors (Huang Liren et al., 1991). As the city developed, more and more ground water was exploited, which increased the rate of subsidence. In most years, more than 100 million tons of ground water are extracted. From 1959 to 1985, 71 km^2 of land in Tianjin had subsided by 1.5 meters, with the maximum subsidence of 2.63 meters. The average rate of subsidence between 1966 and 1990 was -51 mm/year, and between 1980 and 1981, the maximum rate increased to -119 mm/year.

FIGURE 2. ESTIMATES OF FUTURE SEA LEVEL RISE

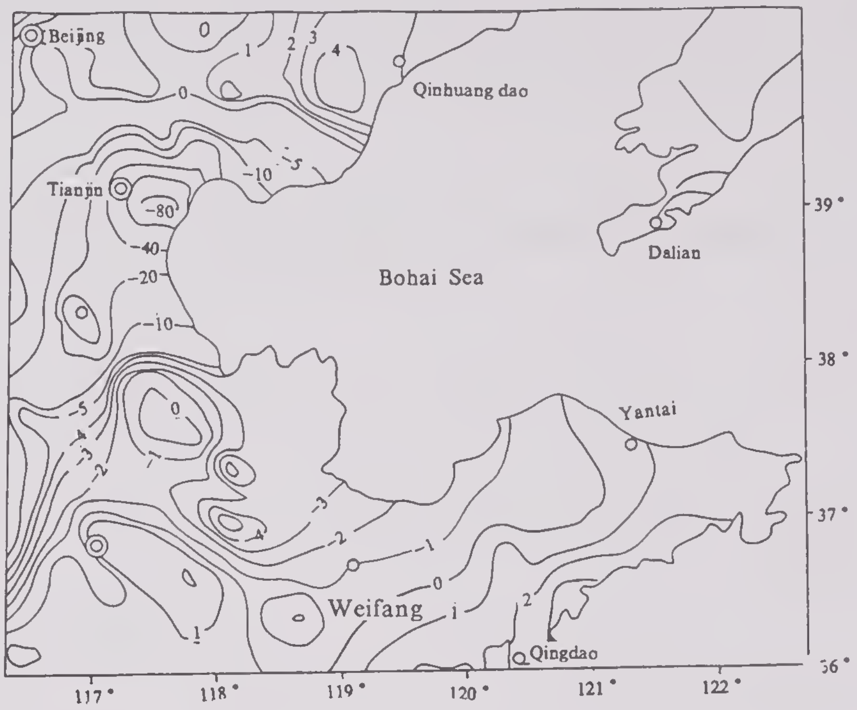


Source: Titus, 1991.

In 1985, the government of Tianjin began to take measures to control the rate of subsidence. The government installed more than 600 wells to stop ground water exploitation. As a result, by 1990, the rate of subsidence had decreased to -9.9 mm/year. Now people in Tianjin are striving to decrease the rate to -5 -to-8 mm/year.

Tanggu and Hangu, which are located close to the Bohai Sea, have higher subsidence rates than Tianjin. In 1984, the land in Tanggu district subsided 137 mm. After instituting control measures for several years, by 1988 the subsidence had decreased to 29 mm. The rate of subsidence in the study area decreases gradually from the subsidence funnels to both northeastern and southern directions. Northeastward to the Luanhe River delta, the subsidence rate has decreased to zero. Southward to the Huanghe River delta, the rate of subsidence has decreased to -3 mm/year, with a maximum of -5 mm/year at some individual places, which may be due to the exploitation of oil and natural gas in the Shengli oil field. In the Laizhou Bay area, the rate of subsidence has decreased from -3 mm/year in the west to -1 mm/year in the east (Figure 3) (Huang Liren et al., 1991).

FIGURE 3. ISOLINES OF RATES OF GROUND SUBSIDENCE (MM/YR)



Source: Wang et al., 1991.

IMPACTS OF THE LANDWARD MIGRATION OF COASTLINES

POSSIBLE POSITIONS OF NATURAL COASTLINES IN 2100 A.D.

In river mouth, the sediment carried into sea by the rivers can push coastlines seaward. Thus, both subsidence and accretion are taken into account in predicting the positions of the coastlines in 2100. Because the period of prediction is quite long, some errors may inevitably exist.

As the sea level rise in the study area in the past 100 years has kept pace with the global rate, it is feasible to adopt the IPCC's 1990 minimum and maximum estimates of mean sea level in 2100: 0.30 and 1.0 meters.

The vertical movement of land (including the effects of both natural and man-made factors) is predicted in the mean values. According to the process of subsidence in Tianjin city in the 20th century and the effects of recent subsidence control measures; it is reasonable to adopt -7 mm/year as the average annual rate. The rate of subsidence in Tanggu and Hangu districts at present varies from -20 to -30 mm/year. This rate will possibly still be relatively high in the next 10 years, but should decrease later. So in the next century we estimate -15 mm/year as the average subsidence rate in the two districts, and -5 mm/year as the average rate in other places of the Bohai Bay coastal area. The rate of subsidence changes gradually from one region to the next.

The sum of the amplitude of global sea level change plus that of the vertical movement of the land is the relative sea level change of the area. Because the present natural coastline is located at approximately 1.5 meters above the mean sea level of the Yellow Sea, 1.5 meters should be added to the above-mentioned predicted relative sea levels to make out the altitudes of the natural coastlines in 2100 A.D. in the study area (Table 4). The Huanghe River delta is an exceptional area, where great amounts of sediment carried by the river are deposited on both the subaerial and subaquatic delta plains. It is estimated that the annual sediment discharge of the Huanghe River in the next century will be 500 to 600 million tons. This rate of deposition will be greater than the rate of relative sea level rise in the next century. Thus, the delta will continue to spread out, and the deltaic coastline will continue to migrate seaward.

TABLE 4. SEA LEVEL RISE AND THE ELEVATION OF COASTLINE IN 2100 (CM)

Areas	**1**	**2**	**3**	**4**	**5**	**6**
Tianjin City	30 100	80	110 180	260 330	200	460 530
Tanggu Hangu Districts	30 100	160	190 260	340 410	200	540 610
Coast of Bohai Bay	30 100	60	90 160	240 310	200	440 510
Huanghe River Delta	30 100	30		150*	250	400
Coast of Laizhou Bay	30 100	20	50 120	200 270	350	550 620

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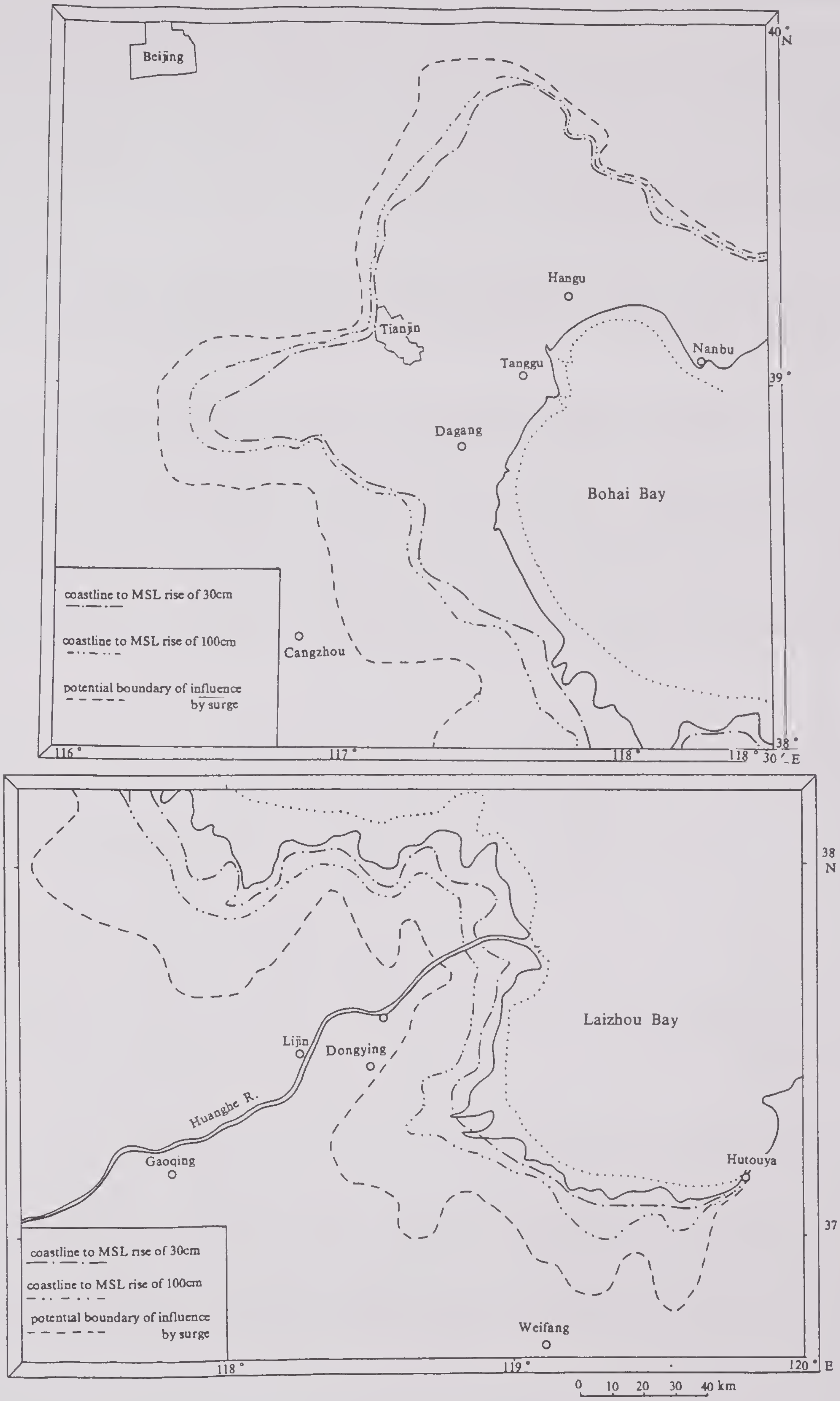
* Assumes that the elevation of coastline in 2100 in the Huanghe River delta is the same as that at present because of the supplies of river sediment.

Key to table columns: (1) Global sea level rise, (2) Ground subsidence, (3) Relative sea level rise, (4) Elevation of coastline in 2100, (5) Setup by surge, (6) Potential range of surge influence.

The study area is severely harmed by temperate-zone storm surges. The potential influence ranges caused by storm surge are determined by adding the maximum height of storm surge setup to the predicted altitudes of the natural coastlines in 2100. For example, the respective maximum heights of storm surge setup are 3.5, 2.5, and 2.0 meters in the Laizhou Bay, in the Huanghe River delta, and in Bohai Bay. If the height of setup in Laizhou Bay in 2100 remains the same as at present, the area under the 6.2-meter contour at present could be inundated by storm surge at that time.

Now we can draw the potential lowest and highest coastlines (Figure 4) and the maximum range under the influence of sea water in case of storm surge in 2100 A.D.

FIGURE 4. PREDICTION OF CHINA'S COASTLINE IN 2100


Beijing
40° N
Hangu
Tianjin
Tanggu
Nanbu
39°
Dagang
Bohai Bay
coastline to MSL rise of 30cm
coastline to MSL rise of 100cm
potential boundary of influence by surge
Cangzhou
38°
116°
117°
118°
118° 30' E
38° N
Laizhou Bay
Lijin
Dongying
Huanghe R.
Gaoqing
Hutouya
37°
coastline to MSL rise of 30cm
coastline to MSL rise of 100cm
potential boundary of influence by surge
Weifang
118°
119°
120° E
0 10 20 30 40 km

ENVIRONMENTAL IMPACTS

The environmental impacts of relative sea level rise in the study area are mainly (1) shoreline retreat and land loss, (2) increased flooding and waterlogging, and (3) saltwater intrusion into soil and ground water.

SHORELINE RETREAT AND LAND LOSS

Vast lowlands lie along the coast to the west of Bohai Bay and Tianjin municipality. Because the rate of subsidence in those two regions is about 2–5 times as high as that of sea level rise, the losses and damages caused by the combined effect of sea level rise and subsidence will be extremely large.

If global mean sea level rises 0.3 meters in 2100 A.D., the coastline in these two regions will retreat by 50 km to the city of Tianjin, which will possibly become the Venice of China. About 10,000 km^2 of land will be inundated by salt water, and the Tianjin-Shanghai railway, which is one of the S–N large arteries of transportation of China will also be harmed. If global mean sea level rises 1.0 meter, the coastline will retreat by 70 km, and about 12,000 km^2 of land will be inundated. In the coastal area to the south of Laizhou Bay, the coastline will retreat landward by 10–15 km in general by 2100 A.D., and about 190–540 km^2 of land will be flooded with salt water (Table 5). Land losses area in the Huanghe River delta will be large only in the abandoned river mouth area, where the coastline will retreat landward by several kilometers.

TABLE 5. LAND LOSS CAUSED BY RISING MEAN SEA LEVEL IN 2100 (KM^2)

	MSL Rise of 30 cm	**MSL Rise of 100 cm**	**Max. Range of Surge Influence**
Coast of Bohai Bay	10,180	11,490	16,030
Coast of Laizhou Bay	190	540	1,700
Huanghe River Delta			3,000
Total	**10,370**	**12,030**	**20,730**

If the effect of the setup of temperate zone storm surge is added to the combined effect of sea level rise and land subsidence, the maximum distance for the mitigation of saltwater transgression on land will be more than 100 km to the west of Bohai Sea, up to 40 km in the south coastal area of Laizhou Bay, and about 30 km in the Huanghe River delta. The total area of land inundated will reach 20,000 km^2.

Increased Flooding and Waterlogging

Flooding and waterlogging will increase for three reasons:

1. The frequency and intensity of storm surges will increase. For example, in Laizhou Bay, if relative sea level rises in 2100 by .50 or 1.2 meters, the maximum high-tide level (4.09 meters at Yangjiaogou station) that occurs once in 100 years at present will occur once every 25 years or 5 years, respectively. Thus, storm surges will increase significantly.

2. The erosional base of rivers and the riverbeds of the lower-reach channels will all be raised, which will impede drainage of the rivers in flood seasons and increase the incidence of flooding.

3. Most of the available sea walls will become ineffective against rising tides.

Flooding and waterlogging will be especially serious in the Tianjin-Tanggu region. In view of the topography and the development of river systems, the Tianjin-Tanggu region is gradually becoming a water-collecting basin in northern China, in which most of the land is close to or slightly higher than the present high-tide level. The low surface relief is extremely unfavorable for the drainage of flood waters. Once a catastrophic flood occurs, the Tianjin-Tanggu region will inevitably be inundated. The calamity of flooding will be the first disaster in Tianjin Municipality in the future.

The lower reach of the Huanghe River has become a well-known hanging river above the ground, which constitutes the dividing crest between the Huaihe River and Haihe River systems. The riverbed in the deltaic area is 2–4 meters higher than the ground surfaces beside both of its banks, and the bed of the river section upstream from the deltaic reach may be 10 meters higher than the ground beside the river banks. Sea level rise will no doubt enhance the threat of flooding of the Huanghe River.

Saltwater Intrusion Into Soil and Ground Water

Rising sea level lowers the relative ground-water table, allowing the underground saltwater wedge to advance landward. The penetration of salt water into the land will destroy valuable farmlands and cause severe shortages of fresh water.

These impacts are extremely serious in the southeast coastal area of Laizhou Bay. Because the climate in this area has been seriously dry for a long period, the ground water is exploited, excessively lowering the underground water table below mean sea level. Today, the funnel-form area of the ground-water table that is lower than mean sea level amounts to 2,400 km^2, and the lowest ground-water table at the center of the "funnel" is -20 meters. Moreover, this area has been influenced by several storm surges, one of which occurred on April 23, 1969. With a setup of 3.55 meters in the coastal areas of Laizhou Bay and the Huanghe River delta, more than 70 km of sea walls were destroyed in 2–3 hours, the salt water migrated landward for 30–40 km, and more than 4,000 km^2 of land were damaged by the storm surge. Salt water has intruded into 435 km^2 underground, and the mean distance of saltwater intrusion has amounted to 2 km. If we do not take any measure to control or prevent underground saltwater intrusion, the whole area where the ground-water table is lower than mean sea level will be gradually contaminated, and as sea level rises in the future, 2,000 km^2 of the coastal plain will be completely covered by salt water.

ECONOMIC IMPACTS

The study area is an important economic center in the northern part of China. The population of Tianjin is 8 million, and the gross national product in 1990 was 30 billion yuan (about $5.6 billion (U.S.)).

- Tianjin seaport is the main export-import area of Beijing, and all of northern China.
- There are two major oil fields (Shengli and Dagang) in this area that produce 40 million tons of oil product annually.
- The study area has abundant natural gas resources.
- China's six largest saltworks are in this area. They produce 6 million tons of raw salt annually, and the salt chemical industry has been developed there.
- China's largest soda factories, which produce up to 1.5 million tons of soda annually, are located in the coastal areas of Laizhou Bay and in the Tianjin-Tanggu region.
- Agriculture occupies an important position in the regional economy of the study area. About 1 million hectares of farmland are threatened by sea level rise.
- Wheat, rice, corn (maize), and many other crops are grown on these lands. The annual cereal product is about 5 million tons.
- In recent years, aquacultural production, especially Chinese prawn, has developed rapidly in the study area.

The gross value of industrial and agricultural products that are threatened by future sea level rise in the study area is about 65 billion yuan (RMB), or $12 billion (U.S.), and the gross national product is about $7 billion (U.S.). Worst of all is that the 13 million residents in the vulnerable regions will become environmental refugees, which will put great pressure on other regions of China.

RESPONSE STRATEGIES

Because of the study area's economic importance, the sole option is to take various measures to protect it, especially the city of Tianjin. Today China has adopted the response strategy of limiting the exploitation of ground water in order to slow down land subsidence and saltwater intrusion. In response to future sea level rise, we propose a comprehensive strategy composed of building sea walls to protect against rising tides—diverting the Huanghe River's sediment to lowlands, and raising the base levels of buildings.

BUILDING SEA WALLS

The total length of coastline in the study area, extending from Nanbu in the north, along the coast of Bohai Bay, the Huanghe River delta, and Laizhou Bay, to Longkou in the east is more than 1,000 km. About 800 km of sea walls are needed to protect the whole area against rising tides. Of that, about 500 km of sea walls composed of stone and earth, with a top width of 8 meters, a bottom width of 30 meters and a height of 6 meters should be built along the coasts of the Huanghe River delta and Laizhou Bay; this will cost $180 million (U.S.). About 300 km of stony sea walls will be built along the west coast of Bohai Bay, which will cost $320 million (U.S.). The annual gross value of the industrial and agricultural products protected by of the sea wall was about $12 billion (U.S.) in 1990 and will exceed $25 billion (U.S.) in 2000. Thus, the $500 million cost of constructing the sea wall accounts for only 4 percent of the gross value in 1990, and only 2 percent of that in 2000. Moreover, 90 percent of the coastline in the study area is diked with sea walls of different qualities, and most of them are earth dikes covered by stones. So the actual cost of building the sea wall can be reduced. Furthermore, the project will be implemented over several years, so it will not create a very large financial burden for the government. And once the sea wall is constructed, it will benefit the study area for 100 years. The alternative of abandoning the land of this area is unthinkable for the densely populated China .

DIVERTING THE HUANGHE RIVER'S SEDIMENT

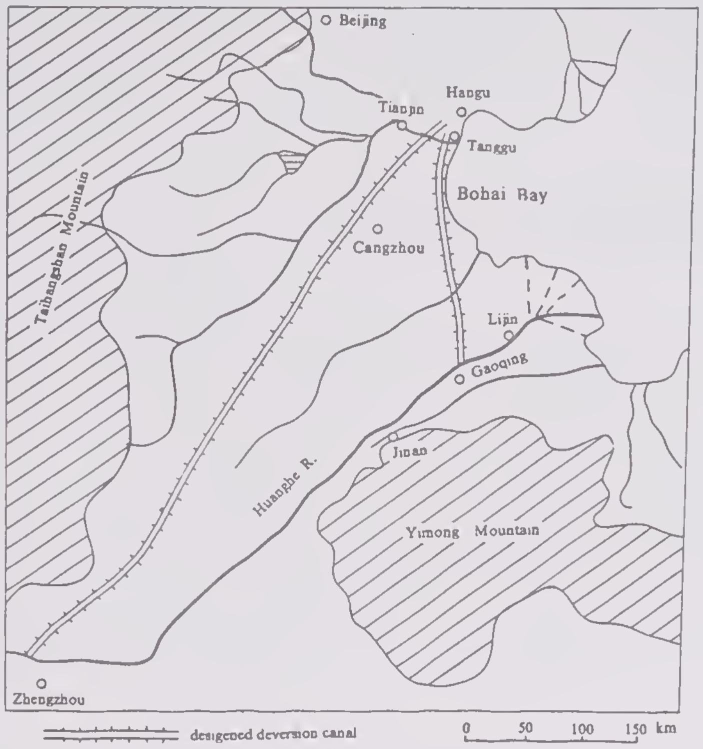
The Huanghe River, which has the highest sediment load in the world, enters the sea between Bohai Bay and Laizhou Bay in the study area. Its average annual sediment discharge is about 1 billion tons. The average sediment content of the river water is 25 kg/m^3, with a maximum of 222 kg/m^3 (1973.9.7). Calculating based on the average value, 1.6 cm thick of sediment layer can be deposited from 1 meter thick of the Huanghe River water. A plain reservoir in the Huanghe River delta region has been built to store water and settle suspended sediment. This measure has not only brought fresh water to the region, but has also silted farmlands. Once the bottom of the reservoir is silted up with sediment to a certain height, another lowland will be chosen to build a new reservoir. This measure can also be used to silt up the lowlands in the Tianjin-Tanggu region.

The channel of the Huanghe River near the apex of its delta is only 200 km to Tanggu—much nearer to the North and South Dagang regions to the south of Tianjin City, and 60–120 km to the bayhead coastal plain of Laizhou Bay. So the distances of drawing water from the Huanghe River to silt up the coastal lowlands will not be very long. In addition, the Huanghe River is an overground river. The elevation of the riverbed near Gaoqing upstream from the apex of the delta is 15 meters (the ground elevation outside the banks of the river is about 5 meters), and the water level of the river is 18 meters higher than the ground in Tanggu and Hangu. So the longitudinal gradient of the diversion canal is about 0.01 percent. If 1/10 of the sediment discharge of the Huanghe River is drawn to silt up the coastal lowlands, an area of 50 km^2 of lowland will be silted up for 1 meter each year. The area of land vulnerable to relative sea level rise in the study area is 17,000 km^2, of which only 2,000 km^2 of the Tianjin–Tanggu–Hangu region are at high risk. If sea level rises by 1.0 meter by 2100, and if 1/10 of the sediment load of the Huanghe River is settled in this region each year, the grounds of the lowlands in the Tianjin–Tanggu–Hangu region will be silted up for 1 meter over an average of 40 years. Thus, the relationship between the ground surface of the lowlands and the sea level in this region in the next century will be maintained at present levels.

In addition, the Yongdinghe River, which is called "the second Huanghe River in China," enters the sea in the Tianjin–Tanggu region. The sediment load in the lower reach decreased as the Guanting Reservoir was built at the upper reach of the river, and the reservoir has been silted seriously. It may be possible to take some technical measures to increase the sediment load of the lower reach of the Yongdinhe River in order to settle more sediment in the coastal lowland.

There are two routes to choose for the project of the diversion canal used to draw water to transport sediment from the Huanghe River to fill in the lowlands in Tianjin-Tanggu region. The first one is from the river section of the Huanghe River near Gaoqing to the coastal lowlands in the Tianjin-Tanggu region. This would entail building a diversion canal from south to north along the present coast. The total length of this canal is about 200 km (Figure 5), which is the shortest route. The second route is from the river section of the Huanghe River near Zhengzhou in Henan province to the lowland in Tianjin municipality. This would entail building a diversion canal in the direction of SW- NE.

FIGURE 5. PROPOSAL FOR DIVERTING THE COURSE OF THE HUANGHE RIVER



In the historical period, the Huanghe River entered the sea through the Tianjin region for a long stage. So diverting the Huanghe River to enter the sea via the Tianjin region completely conforms to the natural law of the river's development. Of course, the artificial diversion of the Huanghe River will force the residents to migrate along the new route. The cost of this impact cannot be calculated accurately. Giving the population density of 400/km^2, 160,000 residents should migrate to other places if the first route with the canal being 200 km long and 2 km wide is selected, and 800,000 residents should migrate if the second route with the canal being 1,000 km long and 2 km wide is selected. If the cost of relocating a person is 20,000 yuan (RMB), the total cost for the migration and resettlement of the residents will be 3.2 billion yuan (about $580 million (U.S.)) for the first route and 16 billion yuan (about $3 billion (U.S.)) for the second route. There will also be industrial and agricultural losses along the route and the engineering cost of the canal. So the project will be very expensive.

On the other hand, the cost of artificially diverting the Huanghe River is much lower than the potential losses caused by the natural breaching of the river bank. From the point of view of long-term interests, the second route—i.e., diverting the Huanghe River from Zhengzhou to Tianjin—is more reasonable. This route not only will relieve the Tianjin–Tanggu region from the threat of sea level rise, but also will improve the conditions of the coastal environment in Tianjin municipality by recharging ground water, which will help slow down land subsidence in this region, and improve the ecological environment along the route at the same time.

RAISING THE BASE LEVELS OF BUILDINGS

Building sea walls and silting up the ground of the lowlands must be accompanied by raising the elevation of the bases of large-scale permanent buildings by about 2 meters. The combination of the three measures can greatly enhance the ability of the Tianjin–Tanggu region to protect itself against the impacts of sea level rise. Applying only one measure without adopting the other two would be ineffective. On this point, the lesson of Mississippi City in the U.S. should be kept in mind. The city is located on the Mississippi Delta, where the ground level is low and subsidence is high. Although the city was enclosed by dikes, they were built many years ago and will be ineffective against flooding. In the next 100 years, the Tianjin–Tanggu region will confront the same predicament as that of Mississippi City, and the situation may be even more severe.

RESPONSE STRATEGIES FOR LAIZHOU BAY AND THE HUANGHE RIVER DELTA

The rate of land subsidence in the coastal area of Laizhou Bay and the Huanghe River delta is merely -2 to -3 mm/year. The relative rate of sea level rise in these two regions in the next century will not be very high. In addition, the ground elevations of these two regions are higher than that of the Tianjin–Tanggu region. Furthermore, the Huanghe River deposits great amounts of sediment there. As a result, these two regions will not be seriously threatened by relative sea level rise in the future.

Based on the past 100 years, it can be inferred that the area of the Huanghe River delta will still increase in the future, but the future rate of accretion may be lower than that the past rate. The measures of building sea walls and main reservoirs that have been used in Huanghe River delta should be continued in the future.

The main problem that the Laizhou Bay coastal area will confront is saltwater intrusion underground. The measures for controlling this intrusion are as follows:

1. Make full use of the freshwater resource of the Huanghe River by building the diversion canal. This project involves drawing water from the Huanghe River at the head of the canal, digging settling basins, and building the diversion sluices. A part of the engineering can make use of the existing project of "Diverting the Huanghe River Water to Relieve Qingdao." The financial investment for the engineering is estimated to be 470 million yuan (RMB).

2. Retain fresh water to recharge ground-water storage and prevent saltwater penetration. This project includes constructing penetrating wells and trenches, river-regulation sluices, underground anti-penetration dikes, and underground reservoirs. During flood seasons, the surface water will penetrate underground through the penetrating wells and trenches to recharge ground water. The fresh water in the sea-reach rivers will be retained by the regulation sluices on the rivers. An underground cement partition dike near the Wanghe River by means of jet-grouting under high pressure will serve as both a dam for the underground reservoir of fresh water and a block against underground saltwater intrusion. The cost of this project is estimated to be 120 million yuan (RMB).

3. Make use of favorable weather to produce artificial rainfall. Airplanes or artilleries can increase precipitation by 15 percent or more. The financial investment of this project is estimated 20 million yuan (RMB) .

4. Limit ground-water exploitation. This measure has been taken.

The government of Shandong Province has organized a team of scientists to investigate the feasibility of controlling the underground intrusion of salt water. The team has submitted its findings to the State Planning Commission, requesting approval of the control project. Comprehensive control of underground saltwater intrusion in the coastal area of Laizhou Bay will cost 610 million yuan (RMB) (about $120 million (U.S.)).

CONCLUSION

The Chinese State Oceanic Administration and the administrative organizations of the coastal provinces and municipalities specialize in the management of the seas and coastal areas. There are 10 scientific research institutions and colleges and universities engaged in the research of sea and coast. The threat of sea level rise has attracted extensive attention of the scientists in China and has been the concern of the governmental departments of oceanic administrations and environmental protection. But as China is a developing country, its finances are limited, and other urgent problems, such as environmental pollution, shortage of freshwater resources, overpopulation, floods, and desertification, compete for limited resources. The potential harmful effects of sea level rise are regarded by the governmental departments as remote problems.

In spite of this, the Chinese State Oceanic Administration and the National Natural Science Funds Commission have organized some small-scale research programs. A number of pilot studies have been carried out on trends in sea level rise and its impacts on local regions. At present, no research is being conducted to assess the nationwide impacts and the losses caused by sea level rise, and no perfect long-term response strategies have been developed. We are striving to apply for a program on these problems and to accomplish this research as soon as possible in order to provide the government with the information it needs to make sound decisions. Only by fully considering the impacts of sea level rise can we effectively carry out the country's modernization.

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ASSESSMENT OF THE VULNERABILITY OF EGYPT TO SEA LEVEL RISE

A.A. Khafagy
Coastal Research Institute
Alexandria, Egypt

C.H. Hulsbergen
Delft Hydraulics
Emmeloord, The Netherlands

G. Baarse
Resource Analysis
Delft, The Netherlands

INTRODUCTION

The Coastal Zone Management Subgroup formed within the Response Strategies Working Group of the Intergovernmental Panel on Climate Change (IPCC) has developed and implemented a methodology for assessing the vulnerability of coastal areas to sea level rise in the context of coastal zone management and planning. During an IPCC meeting in Geneva in August 1991, guidelines were adopted for conducting vulnerability assessments in specific countries and geographic regions. The developed countries agreed to provide technical assistance to developing countries, if required, to help them conduct their case studies (IPCC, 1991).

The Netherlands has agreed to provide such assistance for a number of countries, one of which is Egypt. In August 1991, The Netherlands undertook a short mission to Egypt to formulate the need and possibilities for a vulnerability assessment case study, to develop a preliminary work plan, and to nominate a team of counterparts centered around the Coastal Research Institute in Alexandria (Misdorp et al., 1991). The final approval for the study was given in January 1992. On the Netherlands' side, Delft Hydraulics and Resource Analysis was assigned to assist Egypt in the study.

Subsequently, a mission to Egypt was carried out from January 29 to February 14, 1992. During this mission the advisory panel, the core counterpart team, and a group of local experts were installed, the "Common Methodology" was specified to match the Egyptian circumstances, the work plan and individual tasks were agreed upon, information retrieval was initiated, and a recently established local Geographic Information System (GIS)-team was tapped.

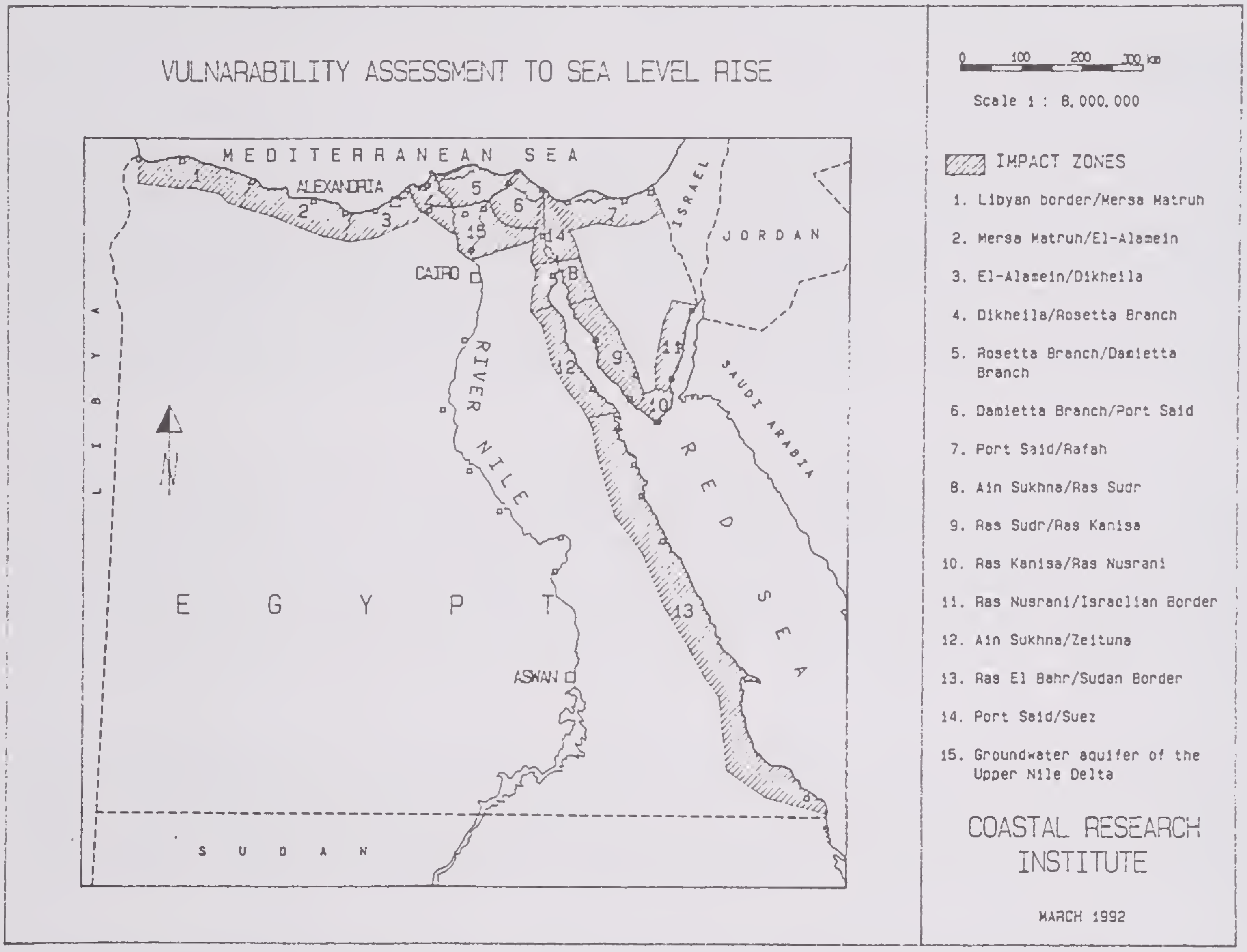
The case study in Egypt has thus barely begun, and it is scheduled to deliver final results by mid-May 1992. Clearly, actual results of the current study are not yet available at this time. This report, therefore, describes the planned study approach, with some specific observations regarding the conditions of the Egyptian coastal zone and presents a number of anticipated impacts. In addition, based on existing knowledge and on recently published reports, it provides a very rough indication of some of Egypt's vulnerabilities.

THE STUDY AREA

The study area includes the entire coastline of Egypt, comprising some 3,500 km of tide-affected coast. From this, 1,000 km comprise primary (i.e., wave-affected) Mediterranean coast; 1,500 km is primary Red Sea area coast (including Gulf of Suez and Gulf of Aqaba), 550 km, secondary Mediterranean coast (lagoons' shorelines); and 450 km, Suez Canal area coast, including the adjacent lakes' shorelines. There is a very large variation in coastal characteristics of these areas and the types and extent of coast-related activities.

This case study focuses mainly (but not exclusively) on the coastal areas of the lower Nile delta because of their importance. The inland boundary of the study area is set at the contour line of +3 m with respect to mean sea level at Alexandria. For practical purposes related to the execution of the study and the presentation of results, the total study area has been divided into the 15 impact zones shown in Figure 1.

FIGURE 1. OVERVIEW OF IMPACT AREAS ALONG THE EGYPTIAN COAST


VULNARABILITY ASSESSMENT TO SEA LEVEL RISE
0 100 200 300 km
Scale 1 : 8,000,000
IMPACT ZONES
1. Libyan border/Mersa Matruh
2. Mersa Matruh/El-Alamein
3. El-Alamein/Dikheila
4. Dikheila/Rosetta Branch
5. Rosetta Branch/Damietta Branch
6. Damietta Branch/Port Said
7. Port Said/Rafah
8. Ain Sukhna/Ras Sudr
9. Ras Sudr/Ras Kanisa
10. Ras Kanisa/Ras Nusrani
11. Ras Nusrani/Israelian Border
12. Ain Sukhna/Zeituna
13. Ras El Bahr/Sudan Border
14. Port Said/Suez
15. Groundwater aquifer of the Upper Nile Delta
COASTAL RESEARCH INSTITUTE
MARCH 1992
MEDITERRANEAN SEA
ALEXANDRIA
CAIRO
ASWAN
RIVER NILE
EGYPT
LIBYA
SUDAN
ISRAEL
JORDAN
SAUDI ARABIA
RED SEA
N

STUDY AREA CHARACTERISTICS

The following sections briefly describe the characteristics of the coastal areas and the 15 Impact Zones that make up those areas.

LIBYAN BORDER - EL ALAMEIN (IMPACT ZONES 1 AND 2)

This high and presumably stable coast is very sparsely populated. It has limited activity directly on the coast, including small-scale agriculture (grazing), and some industrial and fishing activities. It has only one moderately important port (Mersa Matruh) and very limited tourism and recreation in the present situation.

EL ALAMEIN (IMPACT ZONE 3, JUST WEST OF ALEXANDRIA)

This low, coastal desert plain has limestone ridges, expected to be subject to coastal erosion under conditions of sea level rise. In recent years, the building of vacation homes has been booming, to the point where a 500- to 1,000-meter-wide strip directly adjacent to the beach is almost fully occupied with houses and related facilities.

ALEXANDRIA - PORT SAID (IMPACT ZONES 4, 5, AND 6)

The coastal area of the lower Nile delta is to a large extent subject to severe erosion, even without sea level rise. Certain parts of the coast are protected by hard coastal structures, and some beaches are artificially nourished, especially in Alexandria. The area is extensively used for agriculture, in some places almost reaching out to the coastline.

Near the coast, agriculture is confronted with salinity problems, partly caused by the reuse of drainage water for irrigation. A salt wedge from the sea penetrates the aquifer under a 10- to 20-meter-thick clay cap that forms the topsoil of the delta area. In the lower parts of the delta, the saline seepage from the aquifer aggravates salinity problems.

Population densities vary between 200 and well over 1,200 people per km^2 (Aricon, 1989). The two largest biggest cities in the delta, Alexandria and Port Said, are directly on the coast. Alexandria and the surrounding area (Alexandria Governorate) handle 80 percent of the nation's trade and 40 percent of its industry. Some 3.5 million people in the Alexandria area live on 2,700 km^2, and the land elevation is locally 2 meters below mean sea level; about 2 million people live on land that is less than 1 meter above mean sea level (El-Raey et al., 1992). A large number of the fishing ports are located along the Nile delta coast. Within the low-lying coastal zone of the delta are some large, shallow coastal lakes, Burullus and Manzala being the largest. These lakes, which have narrow connections with the Mediterranean, supply a considerable part of the nation's fish production. Some important tourist areas can be found on the delta coast, such as in the Alexandria, Baltim, and Port Said areas.

PORT SAID-ISRAELIAN BORDER (IMPACT ZONE 7)

This low, sparsely populated coastal plain is in part subject to coastal erosion. Some activity occurs directly on the coast, including some small-scale agriculture, mining, and fisheries. Tourism and recreation are still quite limited in the present situation, with El Arish as a regional center, which is also a fishing port. Bardawil Lagoon is used for fishing, but is less productive than the other lakes in the Nile delta.

EAST AND WEST SINAI COAST (IMPACT ZONES 8, 9, 10, AND 11)

The coastline around the mountainous Sinai peninsula is very rugged. Considerable parts of the coast are naturally defended by coral reefs. Mangroves are also present. The whole of the Sinai area is very thinly populated, with limited activity directly on the coast. Agriculture (grazing) mainly takes place in the uplands, and there is limited oil and fisheries activity. The potential for tourism and recreation is very great, but the present number of tourists is still quite limited.

MAINLAND GULF OF SUEZ AND RED SEA COAST (IMPACT ZONES 12 AND 13)

Like Sinai, the coast in this area is rugged. The relatively long, narrow beaches presumably are fairly stable, being naturally protected by large stretches of coral reefs. Also, the Red Sea area is very thinly populated, with agriculture hardly present, and no industry, except for some mining and oil activities. The fisheries production is modest, but has growing potential. The tourism potential is very large, and local centers have recently started to develop (such as the Hurghada area). A few commercial and fishing ports are present along the coast, with Safaga being the most important one.

SUEZ CANAL WITH ADJACENT LAKES (IMPACT ZONE 14)

Since the Suez Canal and adjacent lakes are openly connected to the Red and Mediterranean Seas, sea level rise will have a direct impact in this area. The area is rapidly developing, with thriving tourist and industrial activities. The port of Suez is very important economically, whereas Lake Bitter is important from an ecological point of view.

GROUND-WATER AQUIFER OF UPPER NILE DELTA (IMPACT ZONE 15)

The ground-water resources of the upper Nile delta are a very important source of water. The effects of sea level rise may be harmful to the potential extraction of ground water, which should be carefully considered. The water is and will be used for domestic, industrial, and agriculture supplies. Any reduction of ground-water potential will presumably be at the expense of agricultural uses.

DEVELOPMENT FACTORS

In Egypt, many current conditions and planned activities will have a strong impact on the activities in the coastal zone and, hence, on the future vulnerability to sea level rise. These factors include:

- A strong population growth rate (at present 2.3 percent per year), which will cause almost a doubling of the total population in 30 years (about 100 million in 2020).

- A large planned increase of the cultivated land area by land reclamation, especially in the low-lying coastal areas, west as well as east of the Suez Canal (over 125,000 hectares).

- A shift from traditional fisheries practices toward fish farming in the coastal lakes and other locations at the coast, which will have a very large impact on fish production potential.

- A very strong development of tourism and recreation potential along virtually all of Egypt's coastline, with specific emphasis on the Sinai and Red Sea coasts.

- Expansion of industrial facilities and ports.

In addition, a number of large-scale (potential) projects will affect the development of Egypt's coastal area in the lower Nile delta. These include:

- The construction of one or more reservoirs in the coastal lakes to store fresh Nile water, which is now useless and is released during the irrigation winter stop.

- The construction of the El Salam Canal to supply the North Sinai with irrigation water from the Nile, mixed with drainage water from the lower Nile delta.

- The construction of a highway along the coast of the lower Nile delta.

POTENTIAL IMPACTS

As a consequence of sea level rise, the following impact groups will be considered.

- *Values at loss*, which can occur in several ways:

  —Loss of area because of accelerated coastal erosion (retreat of coastline);
  —Loss of area because of (permanent) flooding of land areas; and
  —Damages because of a direct exposure of structures/facilities to sea conditions.

- *Values at risk* because of changes of flood risk and/or values that are subject to flood risk.

- *Values at change*, because of changes in physical conditions of land and water systems, such as salinity, water levels, drainage, and water discharge.

In principle, the case study will take the following types of values into account: (1) people, (2) capital values, (3) ecological values, and (4) subsistence values. Subsistence values relate to the number of people who can make a living from "free" land resources that may be at risk or lost. Because this life style is hardly present in Egypt (except maybe for some activities in the coastal lakes), it will not be included in the case study.

All of the above values are associated with specific impact categories, such as human activities and facilities, or the natural characteristics of coastal areas. In this respect, Table 1 shows the main impact categories to be considered in the case study. It will be used as a basis for assessing the impacts to be shown in the vulnerability assessment. In principle, all impacts will be determined for all of the 15 impact zones. However, certain impacts are not relevant for the greater part of the Egyptian coast (such as the impacts related to flood risk and the changes in hydrologic conditions of land and water systems, which merely apply to the lower Nile delta). The actual vulnerability assessment table to be produced is based on the summation of impacts across the 15 impact areas, providing an overall vulnerability profile for Egypt.

TABLE 1. RELEVANT IMPACT GROUPS BY IMPACT CATEGORY

Category	At Loss	At Risk	At Change
Population		*	
Residential Area	*	*	
Agriculture	*	*	*
Fisheries/Aquaculture	*		*
Industry	*	*	
Tourism/Recreation	*	*	*
Ports (incl. fishing ports)	*		
Land-Related Infrastructural Facilities (roads, works)	*	*	
Natural Areas	*		*

ANALYTICAL METHOD

The case study will first focus on quantifying the potential impacts just identified. This section outlines main items to be quantified.

LOSSES OF LAND AND RELATED ASSETS

First the location and extent of land losses from shoreline retreat or permanent flooding need to be determined. Estimates of shoreline retreat follow from an assessment of the dynamic behavior of the various areas along the coast of Egypt, which for the lower Nile delta is reasonably well known (Frihy et al., 1991; Delft Hydraulics and Resource Analysis, 1991). For the other coastal sections, (very) rough assessments need to be made on the basis of typical coastal profiles and expert judgment. Permanent flooding of inland areas is only relevant in the lower Nile delta. This depends on the future water levels at sea in relation to elevations of relevant protected sections.

Land losses should be associated with relevant capital values. These values depend on land use and (fixed) facilities present, which may include:

- Residential area and related housing and infrastructure facilities.
- Agricultural area and related buildings, irrigation, and drainage systems.
- Industrial area with related production facilities.
- Recreation area and related recreational facilities.
- Other infrastructural facilities.

For different types of land use and facilities, typical values should be assessed. Possibly, a limited number of classes of mixed land use can be distinguished to which standard values can be attached—e.g., following the results in the Alexandria Governorate (El-Raey et al., 1992).

DAMAGES OR COSTS RELATED TO DIRECT EXPOSURE OF FACILITIES TO THE SEA

These damages and costs will be based on a fraction of the replacement value of the facility considered to express the additional cost to adjust to sea level rise when the facility is replaced anyway at the end of its normal technical or economic lifetime.

LOSSES OF LAND AREAS WITH ECOLOGICAL VALUE

An inventory should be made of all coastal areas with specific ecological value. Given the location and extent of land losses as they may occur, it should be determined if, and to what extent, areas of ecological importance could be directly lost.

CAPITAL VALUES AT FLOOD RISK WITH CERTAIN PROBABILITY

Land areas that will not be lost by shoreline retreat or permanent flooding may still be vulnerable to flooding. Such risks will be present if the land elevation is below more or less extreme water levels as they may occur in view of the (changes of) hydraulic boundary conditions imposed by the sea. Moreover, the relevant coastal protection sections may be at risk of failing, in which case the land will be highly vulnerable to flooding. Capital values associated with the vulnerable land will be multiplied with the probability of flooding, to express the value at risk. Capital values are to be assessed in the same way as mentioned under "Losses of Land and Related Assets."

PEOPLE AT FLOOD RISK WITH CERTAIN PROBABILITY

The procedure to assess people at risk is the same as under 4, but now the number of people in the vulnerable area(s) is multiplied with the flooding probability.

ECONOMIC IMPACTS OF CHANGES IN AGRICULTURAL PRODUCTION

Accelerated sea level rise will likely have various economic impacts, including the following:

- Loss of investments in agricultural land becoming unusable.
- Production losses because of deteriorating salinity and drainage conditions.
- Additional costs of irrigation, drainage, and pumping.
- Cost of supplementing scarce water resources.

A sea level rise will result in an inland movement of the salt wedge in the aquifer below the delta clay cap, increasing both the quantity and the salinity of the upward seepage. These changes in the salinity of the lower delta area will affect present and future agriculture practices. From the assessment of the most likely response of agriculture to such changes, the economic impacts should be estimated. This procedure includes the following steps:

- Assessment of changes in the salinity of the lower Nile delta.

- Assessment of agricultural responses to the salinity changes.
- Evaluation of the costs and damages associated with the agricultural response.

REDUCTION OF AVAILABLE FRESHWATER RESOURCES

Due to the landward movement of the salt wedge, the amount of fresh ground water available for extraction from the delta could be reduced, although this seems not very likely in view of the present ground-water extraction policies. Given the potentially very serious consequences of a possible reduction of ground-water availability, this matter needs to be considered more carefully.

ECONOMIC IMPACTS OF CHANGES ON FISH PRODUCTION

Fish production potential strongly depends on the area, salinity, and water level of the lakes in the coastal zone. Sea level rise may affect these parameters in various ways, which are not necessarily harmful for fisheries. A rough indication should be given of the effects that will occur under various assumptions regarding the future use and management of the coastal lakes.

ECONOMIC IMPACTS OF CHANGES ON TOURISM AND RECREATION POTENTIAL

Tourism and recreation potential could be diminished by losses of beach area or other relevant areas like coral reefs. Actual losses occur if fewer tourists come to Egypt (or more Egyptians spend their holidays abroad), and/or if tourist investments become obsolete before the end of normal lifetimes. In general, the quantification of such effects is highly speculative. However, it must be determined where and how these effects might become important. Moreover, the extent of the possible effects should be indicated.

CHANGES IN ECOLOGICAL VALUES

Direct exposure to changing hydraulic and morphologic conditions might damage coral reefs, while changes in hydraulic and salinity conditions of lakes may cause a loss or gain of ecological values. Also, insofar as coral reefs protect sand beaches, deterioration of the reefs (or lagging behind, as compared to the rate of sea level rise) might cause subsequent erosion of the then less protected beaches. In turn, the eroded beach sand might harm the reef and mangrove habitats. In addition, there may be other examples of relevant ecological changes. To the extent possible, these should be identified and described, at least qualitatively.

PROBABLE IMPACTS AND POSSIBLE RESPONSES

The following provides a very rough indication of the possible impacts of a 1-meter sea level rise. The discussion distinguishes between the "delta" area and the remaining coast. In this respect the delta area is defined as the area from El Hammam to El Arish, roughly including the impact zones 3 through 7.

LOSSES OF LAND AND RELATED ASSETS

In the delta, substantial erosion should be expected, possibly leading to land losses up to 100 km^2. Some of these losses include valuable residential and recreational areas. The total value of these losses may be on the order of 2 billion Le (Egyptian Pounds; 1 Le = 0.3 U.S. dollars 1992). Erosion along the remaining coast is expected to be quite limited. If it is assumed that average erosion will be some 20 meters along 50 percent of the remaining coast, and land values are on the order of 5 Le/m^2, the total loss will be about 200 million Le.

Flooding may only occur in the delta. The total area below the +1-meter elevation contour is assumed to be about 2,000 km^2. If 25 percent of this area would be unprotected, some 500 km^2 could be permanently flooded. With an average land value of 5 Le/m^2 this would lead to a loss of 2,500 million Le.

For the future, capital values may be easily tripled. In view of the very substantial growth to be expected in tourism and recreational facilities, especially outside the delta, as high as a factor of 10 could be applied to potential losses related to coastal erosion in the remaining coastal areas.

DAMAGES OR COSTS RELATED TO DIRECT EXPOSURE OF FACILITIES TO THE SEA

The facilities subject to direct exposure include ports, aquaculture facilities, and other facilities related to the "hard" parts of the coast. Such facilities are mainly present in the delta. According to a rough inventory, damages may be on the order of 1,500 million Le in the delta (assuming a 33 percent increase of replacement cost). In the remaining coastal sections, this amount is considerably less (about 300 million Le). In the future, both amounts could grow substantially. This growth could be higher in the areas outside the delta, since present activities and facilities are quite limited. Tentatively, a growth factor of 3 for the delta and 5 for the areas outside the delta could be applied.

ECONOMIC IMPACTS OF CHANGES ON AGRICULTURAL PRODUCTION

Impacts on agriculture because of changes of physical conditions will only occur in the delta area. In the event of a 1-meter sea level rise, a part of the agricultural area in the 0 to 3-meter elevation contour could be lost, and other parts could be damaged. A very rough estimate of the area that might become unusable is 100,000 ha. With a total investment of about 40,000 Le/ha, the potential damage could be as high as 4 billion Le. Because of the ongoing land reclamation, this amount could be doubled by 2020.

REDUCTION OF AVAILABLE FRESHWATER RESOURCES

For the time being, it will be assumed that the ground-water resources in the upper part of the delta would not be reduced in the case of a well-managed exploitation of the aquifer.

ECONOMIC IMPACTS OF CHANGES ON FISH PRODUCTION

Fish production potential may be affected in the coastal lakes in the delta area. No effects are expected in the remaining coastal areas. In view of the expected strong development of aquaculture, the positive effects on natural fish resources may be reduced again in the future.

ECONOMIC IMPACTS OF CHANGES ON TOURISM AND RECREATION POTENTIAL

Tourism and recreation potential are in fact likely to be subject to some adverse effects of sea level rise, such as beach erosion and changes of coral reefs or coral islands. In the Alexandria area, the loss of beaches is already a severe problem. The anticipated very strong future developments in this area might enhance this vulnerability and extend it to other parts of the coast.

LOSSES AND CHANGES OF LAND AREAS WITH ECOLOGICAL VALUE

Land areas with distinct ecological value are usually changed rather than lost. In some instances, such losses may occur, however. An example might be the loss of coral islands with very low elevations. Land areas with ecological value might sometimes also be gained. This would happen if the coastal lakes are extended by flooding, increasing the potentially valuable wetland areas. Adverse changes are expected from the exposure of coral reefs and mangroves to increased water levels and wave attack, and from beach erosion. The resulting effects for the delta might very well be positive, while the effects on coral islands and reefs in the remaining coastal sections are expected to be negative. In view of planned developments in the coastal lakes, such as a very extensive growth of fish farms, the potentially positive effects on ecological values in the delta may well be reduced in the future.

COMMENTARY ON IMPACTS AND RESPONSES

The following observations and comments can be made with respect to the above-mentioned preliminary results.

- By far the most important effects will occur in the delta area, especially since certain impacts are not relevant for the coastal area outside the delta.

- For the remaining coastal area, the *increase* of the impacts due to future developments may in fact be more substantial than for the delta area.

- Large losses seem to be associated with coastal erosion and flooding. These could be overcome by coastal protection measures. "Hard" protection measures to maintain acceptable flood risks seem feasible but might be quite substantial. The only effective measure to stop the coastal erosion might be beach nourishment. It is very questionable whether this measure would be feasible for large-scale application. For the future planning of activities along the coast, the use of a safe setback line might be a better solution in this respect.

- The plans related to the coastal highway need very careful consideration in relation to sea level rise. In view of anticipated coastline developments, the highway itself could in fact be quite vulnerable. It could be conceived to integrate the construction of the highway as part of a protection response option. A big question would be how to deal with the coastal lakes, however.

- The effects of deteriorating salinity conditions on agriculture are potentially very large. Appropriate physical measures are not known. The impacts are very much in conflict with the intentions to expand agricultural production potential and the optimal use of the scarce water resources of the Nile. In this respect, the future plans regarding the building of reservoirs in the coastal lakes and the construction of the El Salam Canal to supply the North Sinai need very careful consideration.

- In view of the pressure on agriculture and the use of the Nile water resources, any additional negative impact on the Nile hydrology because of climate effects would be disastrous.

- The possibilities of changing agricultural practices within the coastal zone subject to salinity problems and shifting to other types of food production (such as aquaculture) may have to be seriously considered.

Probably the single most important decision in the perspective of sea level rise deals with the feasibility of the planned strong expansion of agricultural area in the low-lying and salinization-prone coastal zone. Even without sea level rise, the coastal strip is by definition the most vulnerable zone when it comes to its dependence on the irrigation water coming from Central Africa, where freshwater resources might be affected by changes in the political climate (Eid and Hulsbergen, 1991). Accelerated sea level rise and ongoing subsidence will cause ever-deteriorating conditions and may eventually undermine the feasibility of agricultural reclamation projects in these marginal areas. Recent warnings in view of an imminent global freshwater shortage, communicated during the International Conference on Water and Development in Dublin, January 1992, point in the same direction.

Possibly the single most important asset of the sea level rise issue is the compulsory 50- to 100-year time frame, since this forms a stimulating perspective for all kinds of socioeconomic issues that otherwise might easily suffer from being judged in too narrow a framework.

FUTURE ACTIVITIES

Future activities in conducting the case study for Egypt will primarily focus on collecting and processing basic data, and on developing and applying simple quantitative relations for the impact assessment, the response analysis, and a preliminary evaluation of strategies.

A Geographical Information System (GIS) will be used in the case study for storing and processing spatially oriented data. The GIS will serve the following objectives.

- Creation of cartographic maps to be used for presentation of the case study results. These maps will show a general overview of Egypt, the location of the fifteen impact areas considered, as well as the presentation of the results obtained within the case study.

- Performance of a more detailed analysis of the delta area, where flooding and saltwater intrusion are of major interest within the case study. To the extent possible, the analysis will be based on detailed land-use maps and detailed land-elevation data. The GIS will use the elevation data and an inventory of the protection situations of the different areas to obtain maps of areas with different flooding risks. The land-elevation map will also be used to create zones with a high salinity risk due to sea level rise. This information will be combined with the land-use maps to create an overview of the different types of land use in the zones that will be affected by salinity or flooding. In addition, the GIS will be used to create a map of the erosion/accretion along the coastline of the northern delta.

- Furthermore other uses of the GIS in the vulnerability assessment case studies will be explored. Major lines of development here are to be expected in a more accurate analysis and mapping of the salinity and flood risk, based on the linkage of GIS to simple (conceptual) models describing surface-water flow, ground-water flow, and saltwater intrusion.

In accordance with the guidelines (IPCC, 1991) the case study will use two distinct sets of boundary conditions for global sea level rise: a rise of 0.3 meters and a rise of 1.0 meter, focusing on the latter. Subsidence is important in the lower Nile delta and will be taken into account. For the other parts of the coast, there is no indication that any significant subsidence occurs, but this still needs to be confirmed.

Estimates of economic and demographic developments will be used from projections at the national planning level in order to create a future (2020) situation as a basis for the vulnerability assessment according to the guidelines.

A "do-nothing" situation will be used as a reference situation, and a full protection response option will be considered as the other extreme. If possible, the response options "retreat" and "accommodate" will be included in a simplified way, or possibly will be combined in a single option. The estimates of costs and effects of these response options will be based on a very rough approximation.

The interpretation of results is based on a comparison of the vulnerability profile in the reference situation ("doing nothing" in a world without socioeconomic and demographic developments) with vulnerability profiles under different combinations of development scenarios and response options. This means that vulnerability profiles need to be determined for a number of different situations. A simplified automation procedure will be developed to generate the vulnerability profiles for the relevant situations to be considered, based on the processing of the different impacts and responses as they apply in the various impact areas.

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ASSESSMENT OF THE VULNERABILITY OF ORISSA AND WEST BENGAL, INDIA, TO SEA LEVEL RISE

V. Asthana, S. Surendra, and S. Venkatesan
School of Environmental Sciences
Jawaharlal Nehru University
New Delhi, India

INTRODUCTION

With its long coastline and two island groups, India takes a serious view of the possibility of a rising sea level rise due to the greenhouse effect. Consequently, in late 1988 at a national seminar, oceanographers, climatologists, earth scientists, and government representatives resolved to launch a nationwide project to study the impacts of a 1-meter rise in sea level rise along the coasts of India and its islands (Asthana, 1989).

They identified eight groups representing universities, institutes of technology, and research institutions to conduct the study. Two of the eight are analyzing the historical tidal gauge data to determine the long-term trends of sea levels along various sectors of the Indian coast; the other six groups are studying the impact scenarios. An all-India coordination and monitoring unit was also established to oversee and guide the study's progress.

The case study presented here is for the coastal areas of the two states of Orissa and West Bengal, lying along northwestern coast of the Bay of Bengal (Figure 1). Within the confines of these two states lie two large delta systems, an extensive lagoon, and the country's most extensive mangrove swamps. Thus, the area offers a very diverse and challenging set of natural and socioeconomic conditions for impact analysis. It is also one of the relatively poorer areas of the country, especially the state of Orissa.

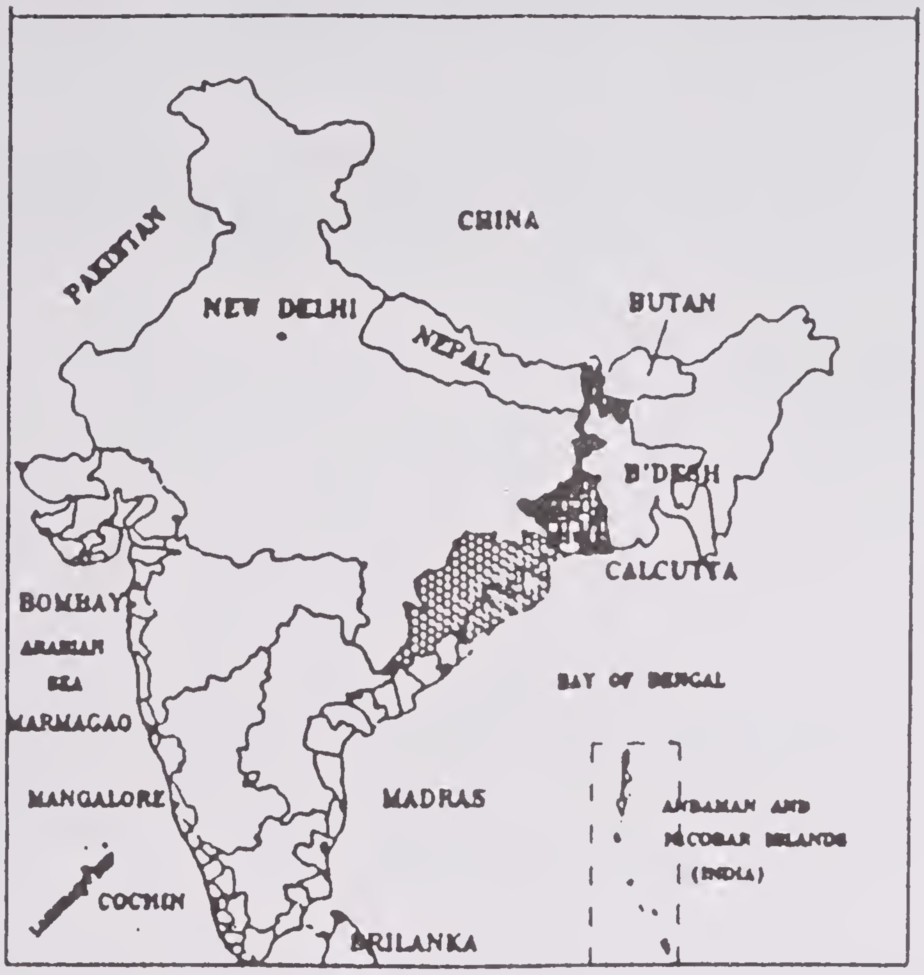
ANALYTICAL METHOD

Since the impact study is being carried out on a national scale, it was considered from the very beginning to follow an agreed-upon common methodology. The project leaders met twice to formulate the methodology and objectives, keeping in mind the data base constraints and local, specific, or unique conditions.

At the time of the project's formation, the most accepted and prevalent scenario of sea level rise was Hoffman's (1983). Accordingly, this study adopted his mid-low scenario projecting a sea level rise of about 1.5 meters by the year 2100. Of course, these projected estimates have been scaled down, but due to constraints of the unavailability of sufficiently large-scale topographic maps, it was considered that any attempt below a 1-meter elevation would be highly prone to error. Thus, we have studied impacts up to a 1-meter rise in sea level.

As mentioned earlier, the topographic maps of the Indian subcontinent are largely available at 1:50,000 scale with a 20-meter contour interval. A very limited section of the national coastline

FIGURE 1. THE STUDY AREA



is covered by 1:25,000 scale with a 10-meter contour interval, and no maps are available for the study area reported here.

A 1-meter contour was drawn using spot height, benchmark elevations, a limited field survey, and the existing contour lines on the map through the process of interpolation. Digital Terrain Modeling algorithms were tried to draw the 1-meter contour; however, an extremely low density of elevation data produced unrealistic terrain models.

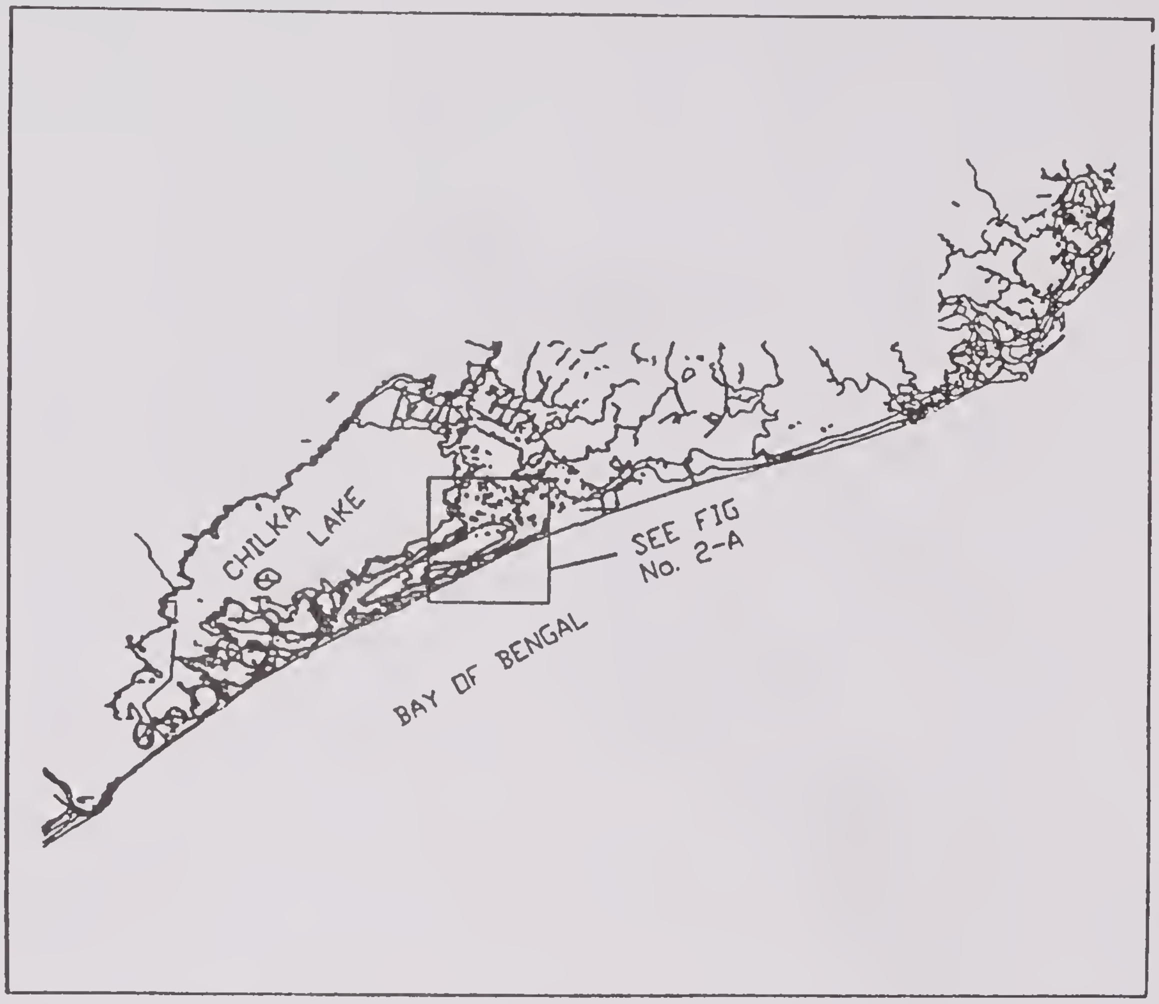
Socioeconomic, demographic, and land-use data have been obtained from the 1981 Census of India. Although the Census for 1991 was completed in March 1991, since much of the village-level data are yet to be published, this study could not use the latest data. Thus, the data in this report represent the district level. Agricultural output data have been obtained from District Statistical Handbooks and the Annual Report of the Directorate of Economics and Statistics, Ministry of Agriculture.

THE STUDY AREA

The states of Orissa and West Bengal lie along the east coast of India bordering the Bay of Bengal (Figures 1–5). The southern boundary of the study area lies in the district of Ganjam, Orissa (Figure 2), and the northern boundary in the region of the Gangetic delta bordering Bangladesh (Figure 3).

The study area has two very large deltas: the Mahanadi, Orissa (Figure 4) and the Ganga-Brahamputra, W. Bengal (Figure 3). One of the largest lagoons of the subcontinent, Lake Chilka, also falls within the study area (Figure 2). The district of Baleshwar, Orissa, is also part of the study area (Figure 5).

FIGURE 2. CHILKA LAGOON – GANJAM AND PURI DISTRICTS, ORISSA

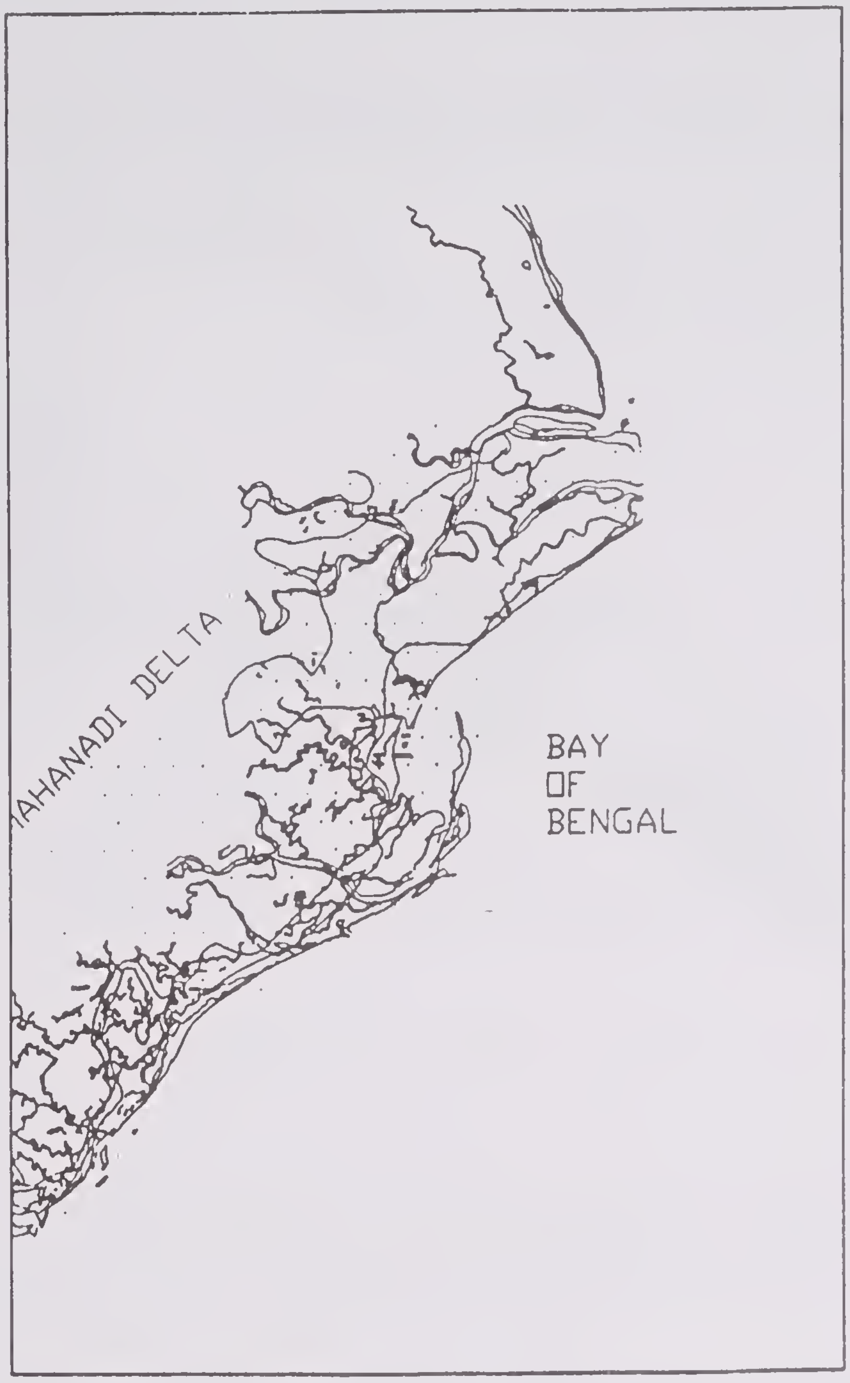


CLIMATE FACTORS

The study area has a hot, tropical climate characterized by oppressive summer, low daily range of temperatures, and high humidity and annual rainfall. The mean annual temperature for the region is 25–26° C. The mean annual rainfall varies from 1,400 mm in the southwest to 1,800 mm in the northeast. More than 80 percent of the precipitation occurs during the southwest monsoon (Sing, 1971).

Approximately a 25-km-wide belt along the area is vulnerable to cyclone hazards, the risks being particularly severe at the mouth of rivers. The district of Twenty Four Parganas has been visited by cyclones on 23 occasions between 1889 and 1988.

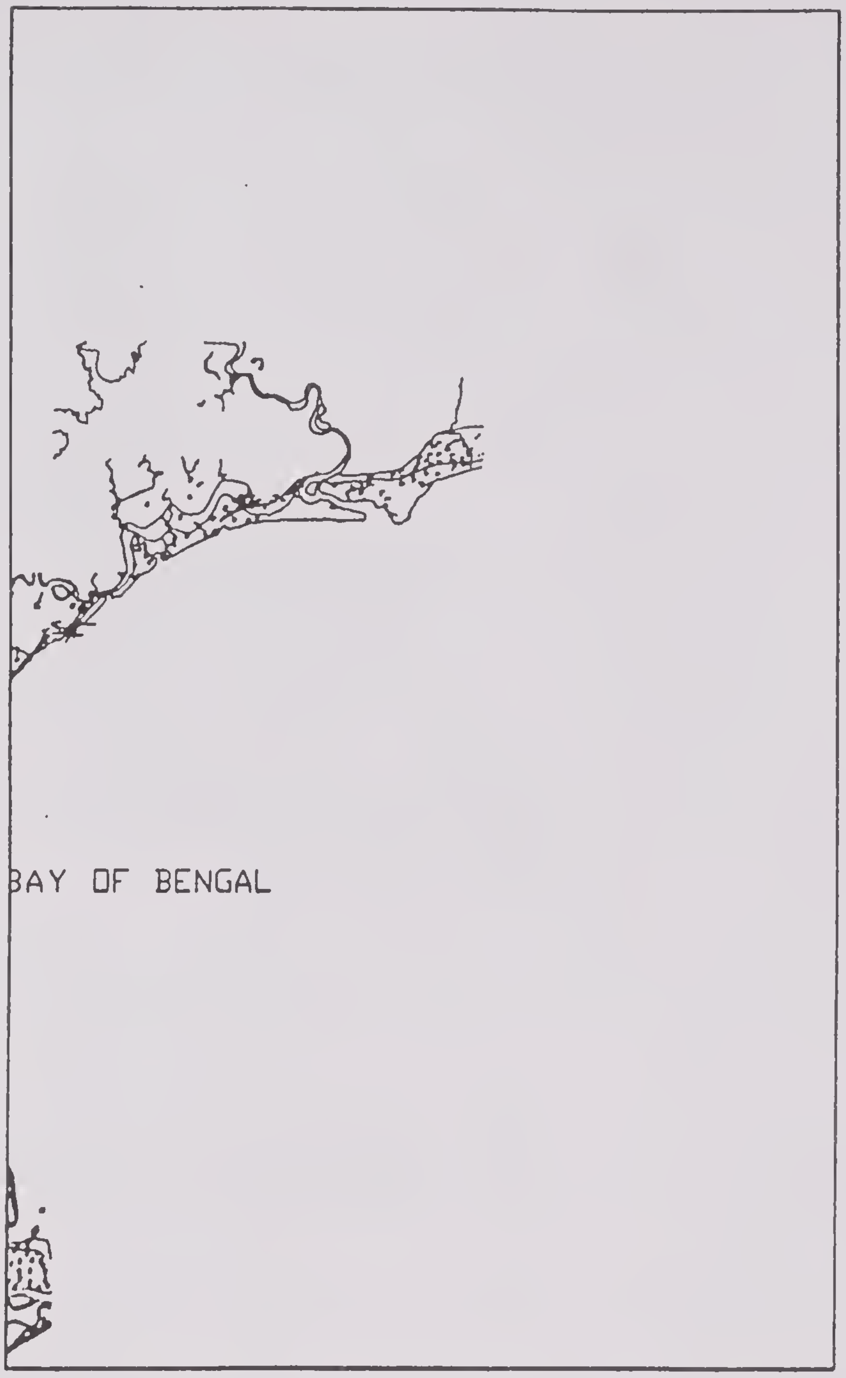
FIGURE 3. MAHANADI DELTA SYSTEM – CUTTACK DISTRICT, ORISSA



NATURAL SYSTEM CHARACTERISTICS

As seen in Table 1, the most salient features of the study area are its two very large delta systems and extensive mangrove swamps. One of the natural systems of great ecological significance are the mangrove swamps bordering the two deltas (Figure 3). If the Sunderbans mangrove swamps of India and Bangladesh are taken as a single entity, which they are, then they represent one of the largest mangrove ecosystems in the world (8,000 km^2: 6,000 km^2 in Bangladesh and 2,000 km^2 in India; Naskar and Guha Bakshi, 1987). In the event of a sea level rise of any magnitude, preserving this large and unique ecosystem will be one of the biggest challenges, considering that these forests are already highly vulnerable because of human activities.

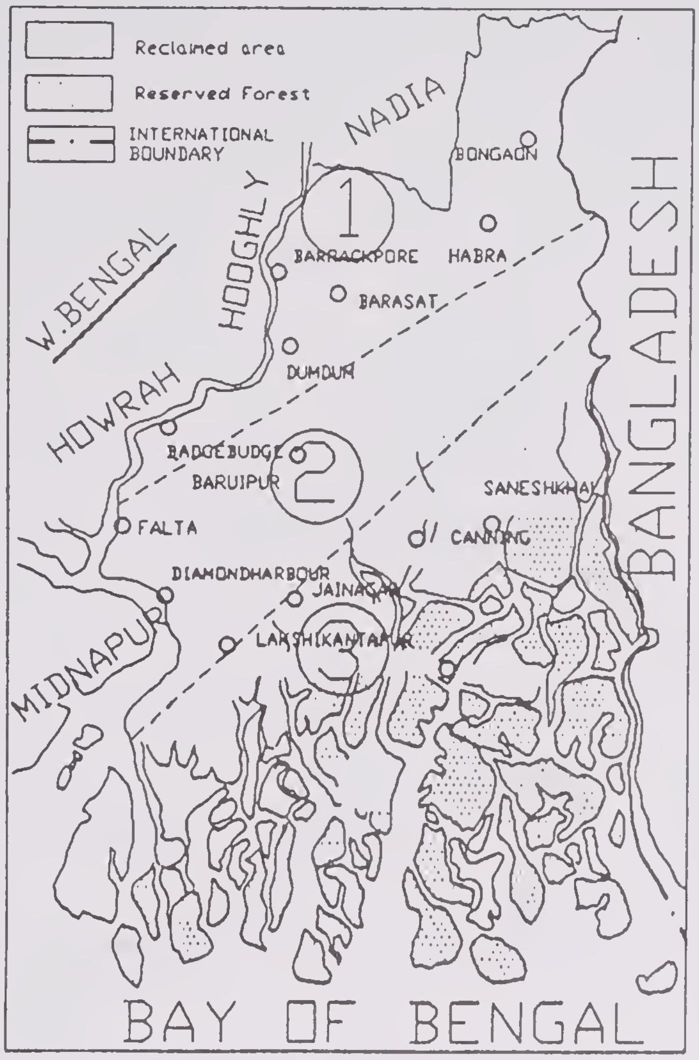
FIGURE 4. DISTRICT BALESHWAR, ORISSA



Due to rapid delta formation, the Sunderbans on the India side are in a dynamic state (Morgan & McIntire, 1959). This part of the mangrove forest is of recent origin, being the alluvial plain of lower Bengal raised 6–9 meters above mean sea level due to the accelerated deposition of sediments brought from the rapidly eroding mountains (Naskar and Guha Bakshi, 1987). It has been estimated that about 6,000–7,000 years before the present, the entire Sunderbans area was under the sea (Chand, 1977). Pollen analysis (C^{14}) dating and study of the peat soil indicate that the present metropolis of Calcutta was under the mangrove swamps about 5,000 years before the present (Ghosh, 1941; Chanda & Mukherjee, 1969; Sen and Banerjee, 1984).

A complex interaction of such factors as neotectonism, rapid siltation and consequent shifts of the tidal channels, land formation vis-a-vis desalinization of the lower Gangetic delta, and heavy population pressure has resulted in the reclamation of ever-expanding agricultural lands, and lately areas of extensive fish farming. These flat, reclaimed lands have been protected against saltwater inundation by embankments or dikes. They are generally 1 meter above the high-water level and run a total length of 3,500 km (Gregory, 1975).

FIGURE 5. GANGETIC DELTA SYSTEM – SUNDERBANS, WEST BENGAL



Zone 1: Mesophytes
Zone 2: Mesophytes and Halophytes
Zone 3: Halophytes

The evolution, maintenance, and ever-changing morphology of the mangrove swamps are controlled by a dynamic set of natural and human-induced factors. Thus, predicting how natural systems would respond under a rising sea level scenario is an extremely complex process, perhaps requiring a microlevel, detailed study to understand the dynamics of behavior and the responses of the natural and manmade systems. Table 2 summarizes the physical changes and responses of natural systems. Some of the items listed in the table could not be elucidated due to lack of data, especially data pertaining to soil and ground-water salinity. These data are yet to collected from the state authorities.

Another important natural system is Lake Chilka, the brackish-water lagoon that is an important sanctuary for migratory birds and a fish farming center. Both the lagoon and the mangroves are covered under the Ramsar Convention on wetlands. Thus, they may qualify for international technical and financial assistance.

TABLE 1. NATURAL SYSTEM DATA: PHYSICAL CHARACTERISTICS

Type of Data	Units	Data Value
Natural coast types		
Flat/sandy (beaches/dunes)	km	680
Flat/mud (salt marshes, mangrove swamps)	km	80
Cliff soft	km	--
Cliff hard	km	--
Glaciated/periglaciated	km	nil
Lagoon/spit	km	540
Barrier coast	km	--
Estuarine/deltas Mahanadhi and Ganges	km	1,075
Coral reefs	km	nil
Artificial coast types		
Sea dikes/sea walls	km	3,879
River dikes/revetments	km	--
Detached breakwaters/groins	km	--
Others	km	--
Local subsidence at different locations		
Natural subsidence	mm/yr	--
Man-induced subsidence	mm/yr	--
Design water level at different locations	m	--
Flood-prone area (area flooded at design water levels)	km^2	
Average tidal range	m	>=1
Seasonal fluctuation in mean sea level	m	
Annual average wave climate at different locations (Hsing, for structural aspects)	m	Predominant wave direction NE-SW H significant 3-4 m
Design wave height at different locations (Hsing, for structural aspects)	m	
Average annual sediment load rivers Mahanadi	tons/yr	1,083.2
Average annual river discharge (Mahanadi)	m^3/s	33,929
Peak discharge (1 in 100 years) (Mahanadi)	m^3/s	--
Area with potential salinity problems	km^2	--

SOCIOECONOMIC CHARACTERISTICS

Tables 3–5 profile the socioeconomic and demographic characteristics of the study area. Tables 6–7 show that the predominant activities in the area are agriculture and fisheries. Compared to the state-level population density, the coastal sectors have much higher densities, essentially because of the high productivity of the land.

TABLE 2. PHYSICAL EFFECTS AND NATURAL SYSTEM RESPONSES

Type of Effect/Response	Units	No ASLR	ASLR 1	ASLR 2
Physical Effects				
Shoreline development				
Erosion	m/yr			6.9
Accretion	m/yr			
Water levels and frequencies of exceedence				
Salinity				
Salt-wedge penetration in tidal rivers	km			127
Seepage rate				
Seepage salinity				
Natural System Responses				
Production areas lost	km^2			1,583.2
agriculture—low intensity				
agriculture—high intensity				
forestry	km^2			30.7
fisheries	km^2			7,040
Subsistence areas lost				
agriculture—low intensity				
agriculture—high intensity				
Habitats lost				
lagoons and barrier seas	km^2			1,150
coral reefs				
intertidal area				
salt marshes				
mangroves	km^2			2,100
Flooding frequency	yr^{-1}			1.0
Water resource situation				

TABLE 3. SOCIOECONOMIC SYSTEM DATA: GENERAL INFORMATION

Type of Data	Units	Data Value	
		Nation	*Study Area*
Gross Domestic Product	1 c	3007×10^9 (INR)	257×10^9
Population	# people	685×10^6	73.6×10^4
Population distribution in study area			
Impact Zone I	# people	---	---
Impact Zone II	# people	---	---
Impact Zone III	# people	---	---
Etc.	# people	---	---
Capital value	1c	---	---
Agriculture area	km^2	1,420,020	1,583.2
Recent average growth rates:			
GDP	%/yr	5.5	5.0
Capital value	%/yr	---	---
Population	%/yr	2.42	2.32

*GDP figures are for the entire state.

TABLE 4. POPULATION AFFECTED BY A 1-METER RISE: ORISSA AND BENGAL COAST

District	Area in Km^2	No. of Villages		Density of Houses	No. of House-holds	Total Popu-lation	Population Density
		In-habited	*Unin-habited*	*Per km^2*			*Per km^2*
Ganjam	9.4372	4	0	173.57	1,776	9,685	1,026.26
Puri	176.5953	82	4	45.09	10,088	62,195	352.19
Cuttack	177.5041	58	5	29.64	5674	35,435	199.63
Baleshwar	118.3181	30	1	42.89	5,520	33,998	287.34
Medinipur	207.6302	361	0	100.98	21,435	129,825	625.27
24 Paraganas	1,015.8217	167	0	85.49	80,742	465,586	458.33
Total	***1,705.3066***	***586***	***10***	***74.91***	***125,235***	***736,724***	***432.02***

TABLE 5. ECONOMIC ACTIVITY IN ORISSA AND WEST BENGAL

District	% of Marginal Workers to Total Population	% of Non-workers to Total Population	% of Main Workers to Total Population	% of Cultivators to Main Workers	% of Agricultural Laborers to Main Workers	% of Household Workers to Main Workers	% of Other Workers to Main Workers
Ganjam	8.43	61.26	30.31	21.97	7.94	2.32	67.78
Puri	1.56	69.43	29.01	44.37	12.57	1.32	41.74
Cuttack	2.20	69.60	28.20	74.30	15.32	0.81	9.57
Baleshwar	0.90	71.02	28.08	59.83	27.46	0.91	11.81
Medinipur	3.03	74.89	22.08	48.61	24.51	2.89	23.99
24 Paraganas	2.31	72.04	26.02	48.48	40.32	0.78	10.41
Total	**2.38**	**72.02**	**25.83**	**49.63**	**32.85**	**1.18**	**16.34**

The capital value loss in agricultural production is maximum in the four districts of the two states, which are also the sites of the Ganges and Mahanadi deltas, where double or even triple cropping of cereal crops is practiced (Table 8). The area is also highly productive for brackish-water fisheries, such as prawn, but we do not have the requisite production data or monetary value of this activity.

Institutional arrangements (Table 9) for either combating or mitigating the suffering of the affected population are fairly strong, and procedures are clearly laid out. Depending on the scale of the natural calamity, administrative and financial resources can be drawn from the smallest administrative unit—the subdivision of the district—to the federal government. Relief and rehabilitation costs are usually shared between the state and federal governments on an agreed-upon formula.

TABLE 6. SOCIOECONOMIC SYSTEM DATA: USES AND VALUES

Type of Data	Units	Data Values
Land Use—Production		
Agriculture Area	km^2	1,583.2
high intensity (e.g., irrigated)	km^2	--
low intensity (e.g., rain-fed)	km^2	--
Forestry	km^2	30.8
Noncultivable	km^2	383.5
Fisheries	km^2	7,040
Mangroves	km^2	2,100
Land Use—Subsistence Production or Capital Value		
Agriculture Area		
high intensity (e.g., irrigated)	INR/km^2	291,481
low intensity (e.g., rain-fed)	INR/km^2	130,000
Forestry	INR/km^2	52,556
Fisheries	INR/km^2	5,600
Subsistence Value		
Agriculture Area		
high-intensity (e.g., irrigated)	--	--
low-intensity (e.g., rain-fed)	--	--

TABLE 7. LAND USE AFFECTED BY A 1-METER RISE: ORISSA AND WEST BENGAL COAST

District	Area (in Hectares)	Land Use (in Hectares)				
		Forest	*Irrigated*	*Unirrigated*	*Cultivable*	*Noncultivable*
Ganjam	943.72	8.09	222.61	556.85	19.42	199.10
Puri	17,659.53	362.22	218.88	9,043.96	2,915.38	4,322.86
Cuttack	17,750.41	2,071.16	0.00	11,577.26	3,005.25	713.90
Baleshwar	11,831.81	0.00	0.00	11,228.04	1,505.03	686.74
Medinipur	20,763.02	15.76	1,085.06	14,947.80	374.42	4,289.88
Medinipur	101,582.17	615.12	693.73	98,255.61	2,652.99	28,142.17
Total	*170,530.66*	*3,072.35*	*2,220.28*	*145,609.52*	*10,472.49*	*38,354.65*

* The summation of area figures of the district will not tally with concerned land-use figures because the former represent those supplied by the Surveyor General, Govt. of India, and the latter supplied by Director of Land Records and Surveys.

** Cultivable includes current fallows, other fallows, and area sown more than once.

TABLE 8. ESTIMATED PRODUCTION LOSS FROM A 1-METER RISE: ORISSA AND BENGAL COAST (THOUSANDS OF INR)

District	Cereals	Pulses	Oil Seeds	Others	Total	Productivity per km^2 INR
Ganjam	2,427	81	662	650	3820	478,697
Puri	45,744	461	7,742	13,430	67,377	553,268
Cuttack	62,435	806	28,869	9,655	101,765	697,648
Baleshwar	51,708	178	8,521	4,534	64,941	510,021
Medinipur	146,676	0	5,039	32,321	184,036	1,121,691
24 Paraganas	694,377	0	25,152	38,129	757,658	745,726
Total	**1,003,367**	**1,526**	**75,985**	**98,720**	**1,179,598**	**745,166**

* Agricultural productivity per year at current prices.

** Other crops consist of sugarcane, potatoes, and income from forests.

*** Per capita production in [Indian National] Rs.1601/year.

TABLE 9. SOCIAL INFRASTRUCTURE AFFECTED BY A 1-METER RISE: ORISSA AND WEST BENGAL COAST

District	Educational Institutions	Junior School	Secondary Schools	Others	Medical Institutions
Ganjam	6	6	0	0	1
Puri	87	82	5	0	1
Cuttack	55	51	0	4	1
Baleshwar	34	29	5	0	1
Medinipur	202	175	14	13	11
24 Paraganas	485	407	41	37	20
Total	**869**	**750**	**65**	**54**	**35**

The Government of India has declared as the Coastal Regulation Zone (1) the coastal stretches of seas, bays, estuaries, creeks, rivers, and backwaters that are influenced by tidal action up to 500 meters from the high-tide line and (2) the land between the low-tide line and high-tide line. Although certain restrictions have been imposed in these areas, their enforcement is currently weak due to the lack of proper surveys and regulatory authorities.

IDENTIFICATION OF RESPONSE STRATEGIES

At this stage of our study, it is not feasible to specify clear-cut response strategies. From the data available so far, however, this study presents some rough contours of expected responses.

As has been noted, the two delta regions in the study area are heavily populated, and the people depend largely on agriculture and fisheries for their livelihood. Because of the number of people involved (> 600,000 according to the 1981 census), the lack of alternative highly fertile land, and the increasing use of these areas for cultivating highly valued prawns, relocation does not appear to be a possible alternative. Restructuring the socioeconomic base is not feasible either, since the area does not have an alternative resource base for manufacturing or the service sector.

One positive feature that already exists is the presence of an extensive network of flood-protection structures around the most vulnerable areas. Strengthening and raising these already existing structures may considerably help the situation at a minimum cost, as estimated in Table 10.

TABLE 10. RESPONSE STRATEGIES: SPECIFICATIONS AND COSTS

Type of Strategy	Units	ASLR 1	ASLR 2
Retreat (R)			
People transferred to other locations	#		736,724
Protection			
Length of dikes and sea walls	km		3,879
Costs of dikes and sea walls	1c/km		2,320,185

In addition to the two delta regions, a few urban centers—namely, Ganjam, Rambha, Puri, and Cuttack—will require flood-protection structures, as will the Paradeep Port and the Konark Temple, the 12th-century temple dedicated to the sun god, which is one of the India's most cherished monuments. Table 11 presents the costs of upgrading existing flood-protection structures in the low-lying coastal region.

TABLE 11. COST ESTIMATION FOR STRENGTHENING/RAISING EXISTING FLOOD-PROTECTION STRUCTURES

State/ District	2r+1(a)	3r+1	4r+1	5r+1	6r+1	**Total cost (000 INR)**
Ganjam	3.96(b) (8,799.12)(c)	0	0	0	0	8,799.12
Puri	113.67 (252,574.75)		13.64 (57,860.88)	0 0	0 0	495,150.50
Cuttack	55.029 (122,274.43)	38.69 (132,861.46)	7.23 (30,669.66)	0 0	0 0	285,805.55
Baleshwar	38.0259 (84,480.44)	23.57 (80,939.38)	10.71 (45,431.82)	3.12 (17,016.48)	18.0 (196,344.00)	424,212.12
West Bengal	3,500 (7,777,000)	0	0	0	0	7,777,000.00
Total						**8,990,967.29**

(a) Relative height of the existing structure + 1 meter of rise in height.

(b) Length of the existing structure in km.

(c) Figure in parenthesis shows additional cost for raising the structure.

(d) Total estimated cost in INR Rs. 9,000 x 10^6.

CONCLUSION AND RECOMMENDATIONS

The most vulnerable areas identified in the study area are the two delta regions. Included within them are the Sunderbans mangrove swamps and Lake Chilka. The area dominated by agriculture and fisheries will need to be protected, especially in the absence of alternative viable economic activity.

The only distant possibility is the finding of large pools of petroleum/gas, which in its wake may bring different types of employment opportunities. Another development possibility that has been discussed for a long time is the building of a shore-based mill for manufacturing export steel. The requisite raw materials are available at not too far a distance, but the prospects appear to be thin in view of the very large investments required (INR .10x10^7).

From the limited perspective of this regional study, it is difficult to project the assistance needed by the entire nation. However, it is clear from our study that the protection of special and fragile ecosystems would require a great deal of scientific and technical input for their preservation. There is an urgent need in India for an Institute for Coastal Studies. Somehow, blue-water oceanography has commanded more attention and resources than the muddy coastal waters. There is also an urgent need to map the coastal tracts at a minimum scale of 1:10,000, if not larger, for accurate analysis and to decide on response strategies.

We are not in a position to present a vulnerability assessment, as proposed in the IPCC's common methodology paper. The common methodology appears to be applicable to a limited, well-defined area. The data base required to draw up these profiles needs to be extensive and relevant to the items included. Also, we do not understand some of the step-by-step aspects of conducting a vulnerability assessment. We suggest that the IPCC elaborate on this aspect.

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ASSESSMENT OF THE VULNERABILITY OF THE NETHERLANDS TO SEA LEVEL RISE

G. Baarse
Resource Analysis
Delft, The Netherlands

E.B. Peerbolte
Delft Hydraulics
Emmeloord, The Netherlands

L. Bijlsma
Tidal Waters Division
Ministry of Transport and Public Works
Den Haag, The Netherlands

INTRODUCTION

BACKGROUND

The Coastal Zone Management Subgroup, formed within the Response Strategies Working Group of the Intergovernmental Panel on Climate Change (IPCC), has taken the initiative to develop and implement an operational methodology for the "Vulnerability Analysis of Sea Level Rise" in the context of coastal zone management and planning. During a meeting in Geneva in August 1991, it adopted a common methodology for assessing the vulnerability of coastal zones to sea level rise (IPCC, 1991).

This methodology will be applied and further developed in a series of short-term case studies involving a representative sample of various categories of coastal environments. Activities will be executed and coordinated through the Advisory Group for IPCC on Assessing Vulnerability to Sea Level Rise and Coastal Management. This advisory group consists of representatives of Argentina, Australia, Bangladesh, France, Gambia, Japan, Kiribati, The Netherlands, Saudi Arabia, the United Kingdom, the United States, Venezuela, and the United Nation Environment Programme's (UNEP's) Regional Seas Programme. The results of the case studies and an integrating report based on the case studies will be used as supporting documents for the IPCC Assessment Report (February 1992) and will be presented at the United Nations Conference on Environment and Development in Brazil (June 1992). In addition, the results will be used as an input to the Intergovernmental Negotiating Committee (INC) in its development of a framework convention on global climate change.

The vulnerability of coastal areas is considered in the context of climate change, initially focusing on sea level rise and related extreme events, such as storms and storm surges (to be referred to as accelerated sea level rise, or ASLR). The vulnerability to be assessed should reflect a nation's degree of capability to cope with the consequences of ASLR. Vulnerability analysis (VA) is defined as an operational procedure to provide a consistent, quantitative description of a nation's vulnerability to ASLR (IPCC, 1991).

As Chair of the Advisory Group, The Netherlands has agreed to provide assistance for the execution of VA case studies in a number of countries, including Poland, Egypt, and Bangladesh. In addition, a VA case study is being conducted for The Netherlands itself. This study was initiated and funded by the Tidal Waters Division of The Netherlands Ministry of Transport and Public Works. Resource Analysis and Delft Hydraulics were assigned to support The Netherlands case study. The study team consisted of:

- Resource Analysis: G. Baarse and W.P.A. van Deursen
- Delft Hydraulics: E.B. Peerbolte, H. Vrijhof, and Th.J.G.P. Meyer
- Tidal Waters Division: L. Bijlsma and L.P.M. de Vrees

The time schedule for the case study was November 1991–February 1992. The present document provides a condensed description of the setup, execution, and preliminary results of this case study. A final report will be prepared in due time.

METHODOLOGY

The Netherlands case study follows the seven steps as outlined in the common methodology (IPCC, 1991). The approach aims to provide:

- A contribution to the development of the common methodology for the execution of VA case studies.

- An automated procedure for the generation and presentation of vulnerability profiles.

- A number of illustrative vulnerability profiles (for different scenarios and response strategies) to actually assess The Netherlands' vulnerability to sea level rise.

A computer model was developed for executing the vulnerability analysis and generating vulnerability profiles. Basically, this model describes the main physical mechanisms and their socioeconomic and ecological impacts, as well as the costs and effects of selective response strategies. The impact mechanisms considered are:

- Water-level changes and coastal erosion leading to changes (shifts) in land and water areas.

- Changes in water-level frequencies of coastal, tidal, and inland waters leading to changes of flood risk.

- Changes in the quantity and quality (salinity) of surface- and ground-water systems leading to water management impacts.

The main part of the model involves a bookkeeping of the flooding and flood risk of land areas and the changes of values associated with these areas. For this purpose, the impact area was broken down into a number of different land and water categories according to flooding frequency. In view of the differences in land-use possibilities and natural characteristics brought about by the flooding frequency, different socioeconomic and ecological values are associated with different land and water categories.

Losses of existing values will occur if the flooding or safety condition changes beyond certain boundaries. If these boundaries are not exceeded, a change in the risk of flooding may occur that will lead to a change of values at risk. Though the principles of such a bookkeeping system may be rather straightforward, there are some complicating factors in the performance of the actual computations, such as:

- Differences in the hydraulic conditions of the various water environments, which may pose a threat to land areas.

- Different types of man-made and natural protection providing various degrees of safety against flooding for specific areas.

- Differences in the topography of specific land areas determining the extent of a flood if flood-protection levels are exceeded.

- Differences in types of land-use and associated economic and ecological values.

In addition to the effects of land losses due to flooding and flood risk, a number of other impacts have been considered in the model, such as:

- The effects of beach and dune erosion.

- Changes in the salinity of fresh surface-water and ground-water bodies.

- Changes in the water management as it relates to drainage and water discharge.

For using the model, a great deal of flexibility is required in order to:

- Assess the impacts of different ASLR scenarios.

- Evaluate the effects of different response strategies.

- Assess the effects of other natural and man-induced future changes.

As this paper notes, all of these factors have been taken into account in the modeling concept as it was developed and applied for The Netherlands.

CHARACTERISTICS OF THE STUDY AREA

The study area includes the entire western and northern areas of the country, which are vulnerable to the impacts of sea level rise—about 60 percent of the country. The eastern and southern parts are at a considerable distance from the sea and are well above sea level. Also included in the impact area are the intertidal areas and the shallow part of the coastal waters (up to a depth of -5 meters). For an overview of The Netherlands and the impact areas, see Figures 1 and 2.

The total land area of The Netherlands is about 37,000 km^2, of which about half is below the present mean sea level and partly reclaimed. The country is densely populated (more than 15 million people, or an average population density of more than 400 people per km^2). The larger part of the country is protected by dikes and a natural dune coast. Some economically important areas (harbors and industrial areas) are outside of this protection system; in the present situation, these areas are generally at sufficiently high elevations to be "safe."

The North Sea coastline, bordering the country in the west and north, is about 350 km long, of which more than 70 percent is natural dune coast. Dikes are present along the tidal and upper rivers, Lake IJssel and Lake Marken, the Wadden Sea, and the estuaries (see Figure 2). Tides generally range from 1 to several meters.

FIGURE 1. OVERVIEW OF THE NETHERLANDS

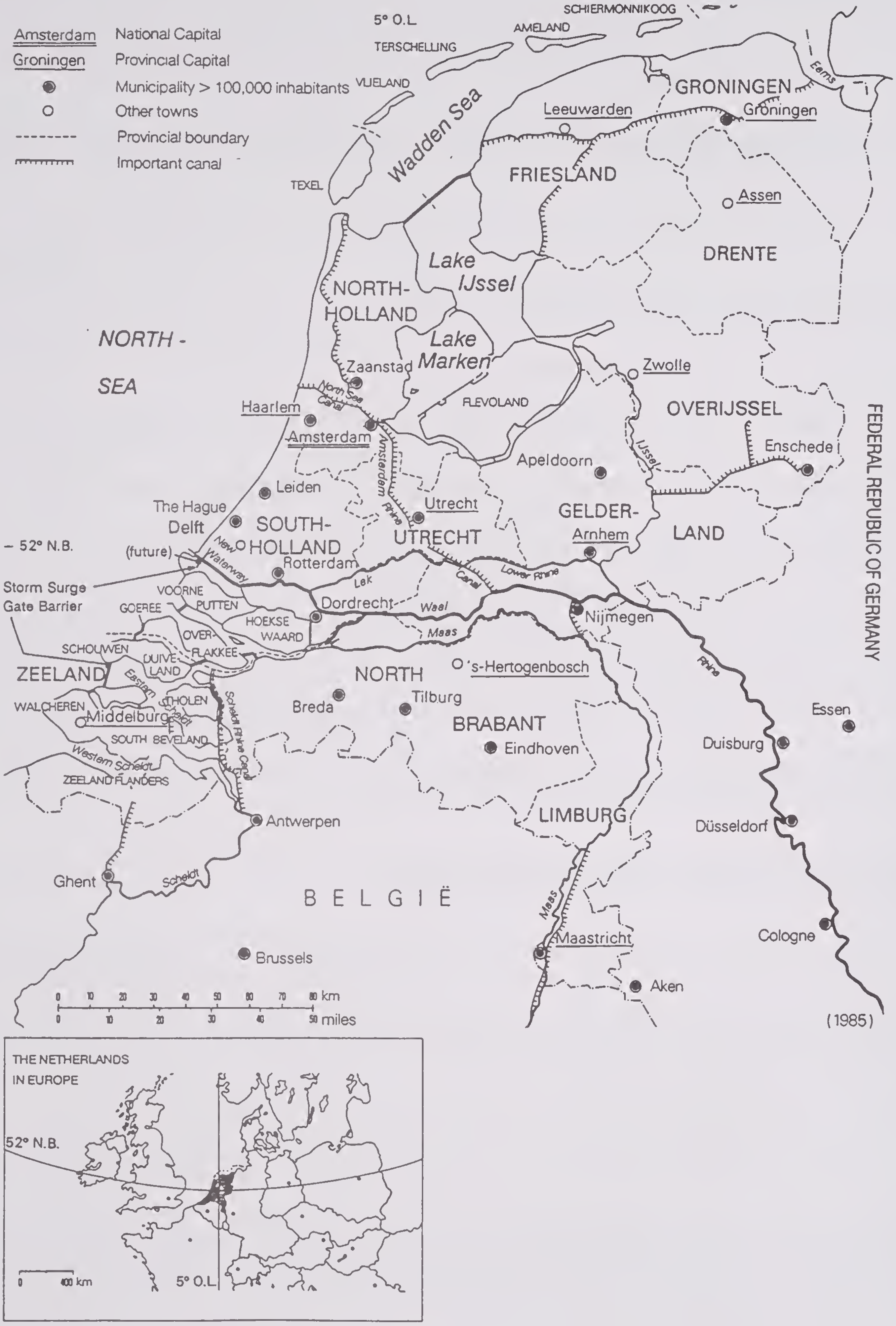
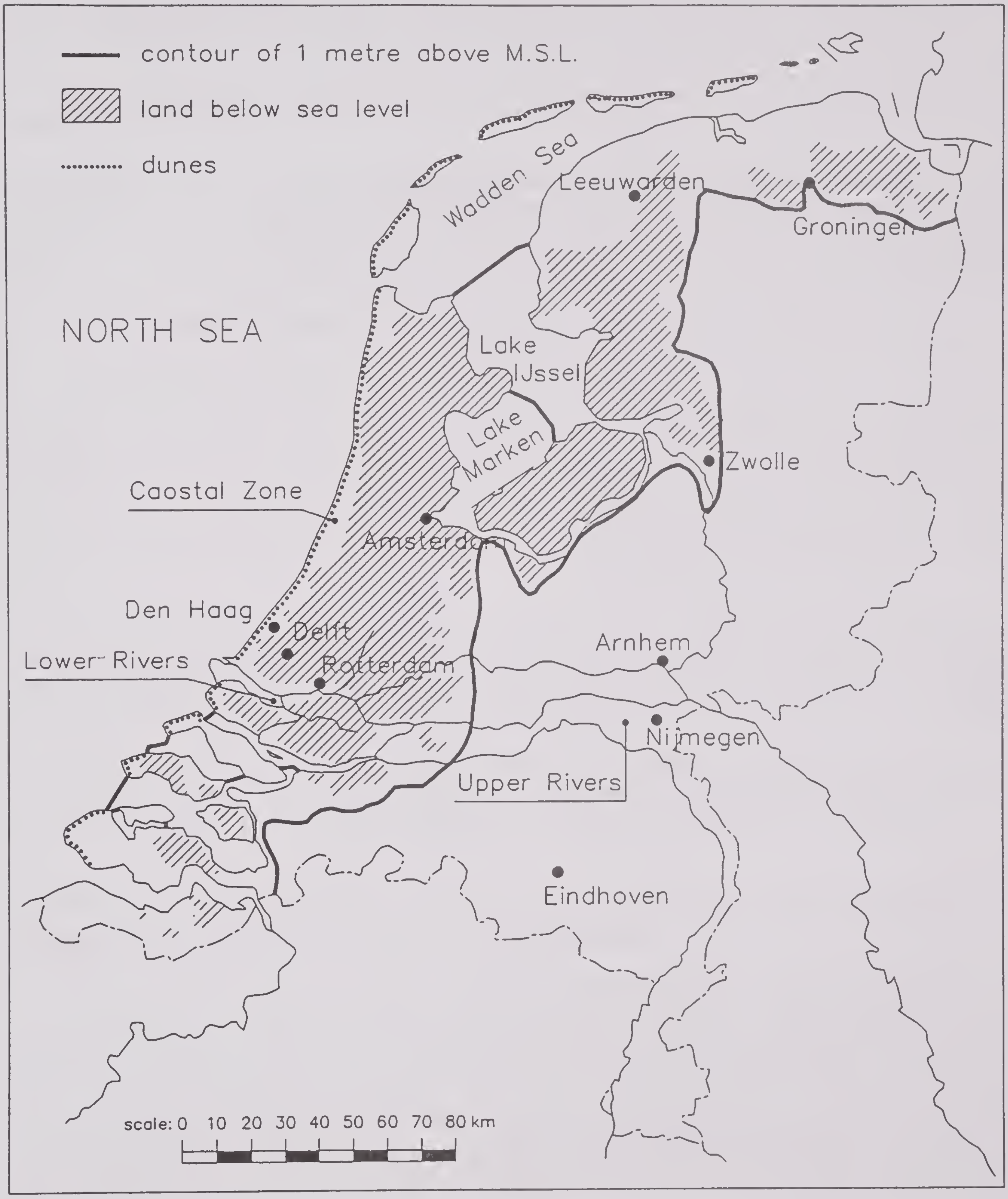


FIGURE 2. OVERVIEW OF THE NETHERLANDS IMPACT AREA



In accordance with the approach as formulated in the common methodology (IPCC, 1991) the following types of impacts will be considered in The Netherlands case study:

- Values at loss, because of area losses and direct exposure to sea conditions.
- Values at risk, because of changes of flood risk and/or values subject to flood risk.
- Values at change, because of changes in physical conditions of land and water systems.

The values to be considered include (1) people, (2) capital values, (3) ecological values, and (4) subsistence values. The subsistence value relates to the number of people who can make a living from "free" land resources that may become at loss or at risk. This is not relevant for The Netherlands.

Assessing vulnerability to sea level rise according to the above aspects requires an inventory of the characteristics of the main impact area, including:

- Flood-protection situation
- Hydraulic conditions
- Topography
- Land use and population
- Infrastructural facilities
- Economic and capital values
- Nature areas and ecological values
- Institutional and organizational aspects

The collection and processing of such information requires a clear definition of the system elements to be considered and a well-organized data structure. In the modeling concept for The Netherlands, a data structure was developed in which the following elements play a key role.

- *Land/Water Categories:* Subdivision of land and water areas into a number of categories according to predefined flooding frequency intervals. For The Netherlands, the following categories were considered: nonflood-prone areas (safe or "dry" land), flood-prone areas (unsafe or "wet" land), intertidal areas, and shallow-water areas.
- *Hydraulic Condition Zones (HCZs):* Water "environments" to which a specific set of hydraulic conditions applies.
- *Geographical Areas:* Spatially determined areas that can be considered homogeneous with respect to the effect of the water environment (HCZ) on flooding probability. A single geographical area can be subject to the hydraulic conditions of more than one HCZ. The total of geographic areas form a complete coverage of the impact area.
- *Protection Types:* Types of protection of geographical areas against flooding. Three types are considered: unprotected, dike, and natural. Examples of natural protection types are dunes, natural ridges, and mangroves, of which only the first is relevant for The Netherlands.
- *Protection Sections:* Different sections (with different dimensions or characteristics) within the same protection type.
- *Subareas:* A further breakdown of geographical areas according to land/water categories and land use (with different socioeconomic and/or ecological values).

Specific topographical conditions can be attributed to each subarea. The exact geographical locations of subareas within a geographical area does not have to be known.

- *Elevation-Distribution Curves:* Curves expressing the topographical characteristics of subareas (percent of area above certain elevation).

LAND/WATER CATEGORIES

The *nonflood-prone area* includes the land area protected by dunes or dikes and the unprotected land area at higher elevations (e.g., more than 4 meters above mean sea level). These areas are usually of great economic importance, capital-intensive, and densely populated. Present flood-protection standards in The Netherlands are very high. Acceptable flooding frequencies are on the order of 1 in 2,000 to 1 in 10,000 years. For this land category, the changes in the capital values and people at risk are determined to assess the vulnerability to sea level rise.

The *flood-prone area* includes the land areas that are generally unprotected and likely to be flooded. Their economic importance is limited (some pasture land and some occasional infrastructure facilities), and in principle no people are living in these areas. These are the marshy and wetland areas that can be found outside the dikes along rivers, estuaries, and the Wadden Sea. Arbitrarily, the flood-prone area was defined as the area that would be flooded from at least once every year to almost every day. Generally the flood-prone areas have a relatively high natural value because of the limited human activities and the dynamic natural processes.

By definition, *intertidal area* is flooded twice every day. Except for typically waterbound activities, such as fisheries and recreation, this area has no economic use. Intertidal areas usually have a very high ecological value, because of their high productivity and specific roles—e.g., bird habitats and fish nurseries.

Shallow water is defined as the saltwater areas that are permanently under water, up to an average maximum depth of 5 meters. This is the area of relatively high turbidity and food concentrations, thus being important for fish and other marine organisms.

HYDRAULIC CONDITION ZONES, GEOGRAPHICAL AREAS, AND PROTECTION SITUATIONS

Assessing the (changes of the) flood risk and flooding situation for the impact area requires detailed information about the hydraulic conditions, the flood-protection situation, and the topography of the area. The hydraulic condition zones (HCZs) are used to express the various sets of hydraulic conditions that might apply to different parts of the impact area. The total impact area is spatially subdivided into a number of geographical areas, each of which is associated with one or more HCZs. Protection sections are in between geographical areas and HCZs. They determine to what extent the hydraulic conditions imposed by the HCZ are actually valid for the geographical area. Several protection sections of different types may apply to each geographical area–HZC combination.

SUBAREAS AND ELEVATION DISTRIBUTION

Differences in land characteristics, land use, and population and related socioeconomic and ecological values are expressed by distinguishing different subareas within the land/water categories of geographical areas. For each subarea, an elevation distribution is specified, based on a number of discrete elevation classes. For a given water-level distribution function to which the geographical area is exposed, the flooding situation of the various elevation classes within the subarea can be determined and, hence, the parts of the subarea that fall within each land/water category (based on flooding frequency). The changes of the flooding frequency situation and the values associated with different subareas according to their land/water category are the basis for the assessment of values at loss and values at risk.

Subareas are considered within land/water categories. Within the nonflood-prone area (dry land), the following types of subareas were distinguished in the model:

• PL	Pasture Land
• AL	Arable Land
• HG	Horticulture Glass
• RA	Residential Area
• HI	Harbor/Industrial Area
• FW	Fresh Water Area
• NA	Nature Area
• MA	Miscellaneous Area (= rest area)

Within the flood-prone area (wet land), the model allows for a number of different subareas to be specified. For the present application, only a single type of subarea was actually considered, however. For the intertidal and shallow water areas, only a single subarea can be specified for each geographical area.

By definition, all areas within the land/water categories wet land, intertidal, and shallow are considered as nature area (area with specific ecological value). Within the dry land category, nature area can be specified as a special subarea. In addition, an ecological value can be attributed to other subareas. This is done by specifying a certain fraction of the subarea to which a dry ecological value should be applied. If desired, the same procedure can be applied to the wet land category. As mentioned before, in the present application for The Netherlands, the wet land category was not further subdivided into subareas.

SCHEMATIZATION AND DATA COLLECTION

As a basis for the data collection, a schematization structure was developed, including:

- 26 geographical areas
- 13 hydraulic condition zones
- 63 protection sections within 3 protection types (unprotected, dune, and dike)
- 139 subareas

Table 1 lists the codes and names of the geographical areas, with reference to the HCZ codes to which they apply. Table 2 lists the codes and names of the hydraulic condition zones, with reference to the geographical area (GA) codes. An overview of geographical area locations in relation to the HCZs is presented in Figure 3.

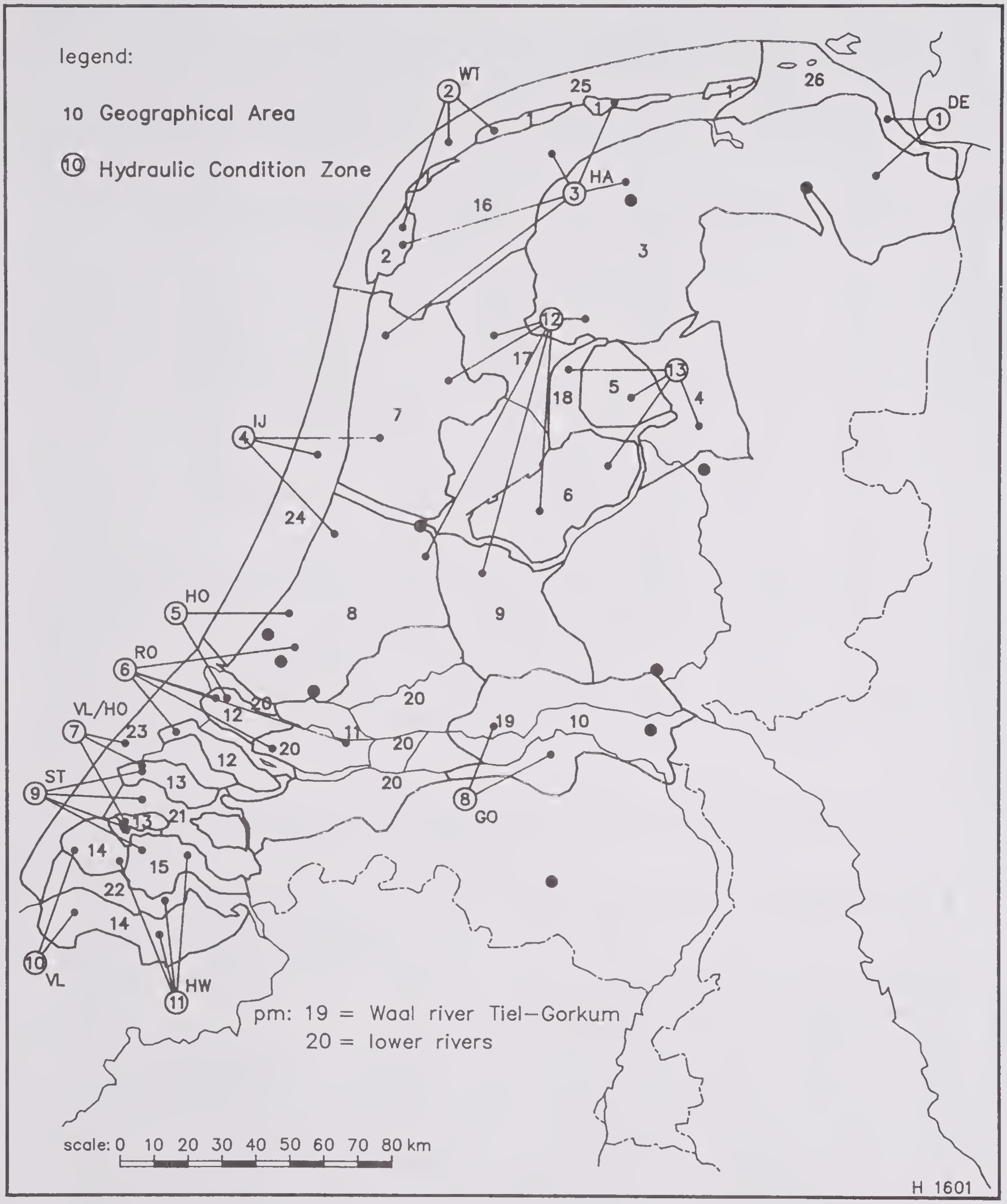
TABLE 1. CODES, NAMES AND HCZ REFERENCE OF GEOGRAPHICAL AREAS

GA CODE	GA NAME	HCZ CODE
1	Small Wadden Islands	2,3
2	Texel	2,3
3	Friesland/Groningen	1,3,12
4	IJssel Delta	13
5	North East Polder	13
6	Flevo Polders	12,13
7	North-Holland	3,4,12
8	South-Holland	4,5,6
9	Utrecht	12
10	Central River Area	8
11	Lower River Area	6
12	Northern Delta Coast	5,6
13	Central Delta Coast	7,9
14	Southern Delta Coast	10,11
15	Inner Southern Delta	11
16	Wadden Sea	3
17	Lake Marken/IJssel N	12
18	Lake IJssel SW	13
19	Upper Rivers	8
20	Lower Rivers	6
21	Eastern Scheldt	9
22	Western Scheldt	11
23	North Sea Delta Coast	7
24	North Sea Holland Coast	4
25	North Sea Wadden Coast	2
26	Delfzijl	1

TABLE 2. CODES, NAMES, AND GA REFERENCE OF HYDRAULIC CONDITION ZONES

HCZ CODE	HCZ NAME	GA CODE
1	Eems/Dollard	26,3
2	Wadden Coast	1,2,25
3	Wadden Sea	1,2,7,3,16
4	Holland Coast	7,8,24
5	North Delta Coast	12,8
6	Rotterdam	8,11,12,20
7	Central Delta Coast	13,23
8	Gorkum	10,19
9	Eastern Scheldt	13,15,21
10	Southern Delta Coast	14
11	Western Scheldt	14,15,22
12	Lake Marken/IJssel N	3,6,7,8,9,17
13	Lake IJssel SW	5,4,6,18

FIGURE 3. LOCATIONS OF GEOGRAPHICAL AREAS IN RELATION TO HYDRAULIC CONDITION ZONES



pm: 19 = Waal river Tiel–Gorkum
20 = lower rivers

An overview of the capital values for the different subareas considered in The Netherlands is presented in Table 3. The first column of the per hectare capital values shown (indicated by CVR) pertains to *all* land values and capital values, including farm buildings, cattle, machinery, means of transport, immovable and movable goods such as private cars, and all people's private possessions in their homes. This capital value is the basis for the assessment of Capital Value at Risk (CVR). The second column of per-hectare capital values represents the capital values that may be at loss (CVL). These values include *only* the immovable capital goods, since one can move out the movable goods before they will be lost.

By far the most capital-intensive area is the Residential Area, to which the bulk of the houses and related facilities and infrastructure was allocated. Other capital-intensive types of areas are: the Harbor/Industrial Area, holding all of the industrial and a part of the transportation/storage investments; the Miscellaneous Area, to which a part of the houses and a lot of the more general infrastructural facilities were allocated; and the Horticulture Glass Area.

The total land-related capital (based on CVR) in The Netherlands and in the impact area (including only the vulnerable part of The Netherlands as represented in the geographical area-schematization) is shown in Table 4. Note that the whole of The Netherlands is worth approximately 4,200 billion guilders (or about 110 guilders per m^2). Not included in the inventory of Table 4 are the large freshwater areas, such as Lake IJssel and Lake Marken.

TABLE 3. CAPITAL VALUES FOR DIFFERENT SUBAREAS IN THE NETHERLANDS

Subarea	**CVR (Kfl/ha)**	**CVL (Kfl/ha)**
Dry Land		
Pasture Land	80	64
Arable Land	80	64
Horticulture Glass	1,200	1,080
Harbors/Industrial	6,930	4,500
Residential Area	9,400	7,050
Miscellaneous Area	2,400	1,800
Nature Area	40	40
Wet Land	-	30
Intertidal Area	-	10
Shallow Water	-	5

The total number of people in The Netherlands is just over 15 million, of which some 10 million people are in the impact area.

All basic data according to the above data structure were obtained from generally available statistical, technical, and geographical information, existing studies (e.g., Delft Hydraulics, 1991), supplemented by specific knowledge and expert judgment of the study team.

TABLE 4. SUMMARY OF LAND-RELATED CAPITAL VALUE IN THE NETHERLANDS AND THE IMPACT AREA

Land Type	Area (ha)		Value (1000 Mfl)	
	Total Neth.	*Impact Area*	*Total Neth.*	*Impact Area*
Dry Land				
Pasture Land	1,096,500	540,400	88	43
Arable Land	893,400	594,000	71	48
Horticulture Glass	9,770	8,870	12	11
Harbor/Industrial	47,800	34,300	331	238
Residential Area	219,500	133,600	2,063	1,256
Miscellaneous Area	670,000	400,000	1,608	960
Nature Area	450,000	198,000	18	8
Wet Land	44,000	44,000	1	1
Intertidal Area	138,300	138,300	1	1
Shallow Water	271,500	271,500	1	1
Total	*3,840,770*	*2,362,970*	*4,194*	*2,567*

ASLR SCENARIOS AND OTHER DEVELOPMENT FACTORS

ASLR SCENARIOS AND NATURAL DEVELOPMENTS

Study boundary conditions include the rate and amount of accelerated sea level rise considered, the rate of subsidence, and the natural development of the dune coast.

In accordance with the common methodology, the case study will use at least two distinct sets of boundary conditions for accelerated sea level rise: a rise of 0.3 meters and a rise of 1.0 meter. However, in view of the modeling concept applied, any amount and rate of sea level rise can be used. The actual amount of ASLR to be used is specified by means of an ASLR scenario, indicating the rate of ASLR in cm per century and the selection of a time horizon T, which in principle can be any number up to 100 years. Multiplying T/100 by the ASLR scenario provides the actual sea level rise (in cm) valid for the situation selected.

Natural subsidence is not significant in The Netherlands (usually on the order of 5 to 10 cm per century); thus, it will not be considered in the study. However, if desired, a value for natural subsidence could be easily included in the ASLR scenario.

The ASLR condition will be combined with the natural development of the dune coast. Based on earlier studies, the development of the dune coast with and without several rates of ASLR was estimated. Taking into account the autonomous development of the dune coast requires selecting a specific point in time for which the vulnerability profile is to be assessed.

HUMAN-INDUCED DEVELOPMENTS

From the economic and demographic data, a selection is made of scenario variables to reflect the most important future developments. In addition to the present situation, based on available projections and policy documents a "future" situation is created. In principle, this future situation is based on a 30-year projection of currently anticipated developments. This future situation should not be regarded as a formal projection, however, but merely as "a possible world of tomorrow" used to show the potential impacts of socioeconomic development on an area's vulnerability to sea level rise. Vulnerability profiles, for different boundary conditions as mentioned above, will be generated for today's world and the "world of tomorrow" in order to assess the relative importance of the various development factors.

The human-induced development variables considered include:

- Population
- Land use
- Capital values
- Domestic and industrial water demand

Official population projections for 2020 show a total population growth between 13 and 21 percent (CBS Population). For the future scenario, a 20 percent growth was assumed. This 20 percent increase was applied to all population densities as compiled for the present situation.

With respect to future land use and capital values, the following assumptions were made based on general observed trends:

Areas	**Values**	
Pasture Land	- 20%	+ 25%
Arable Land	- 20%	+ 25%
Horticulture Glass	+ 20%	+ 50%
Residential Area	+ 20%	+ 30%
Harbor/Industrial Area	+ 20%	+ 50%
Freshwater Area	0%	0%
Miscellaneous Area	0%	+ 30%
Nature Area	Balance	

A reduction of areas is assumed for Pasture and Arable Land, while Horticulture Glass, Residential, and Harbor/Industrial Areas are assumed to grow. The balance of area changes (which is positive) will be added to dry land nature area. Capital value increases are expected for all of the economic land uses. This scenario was implemented by adjusting the areas of the subareas and the related per-hectare values accordingly.

All drinking and industrial water demands were increased by 50 percent.

The above assumptions will lead to an increase of total capital investments in The Netherlands from about 4,200 Gfl to 6,150 Gfl in 2020, at 1990 prices.

Corresponding with these scenario assumptions is an increase of GDP by at least 2 percent per year, which will result in an overall increase in 2020 by 80 percent. This will bring the present GDP of about 500 Gfl (10^9 fl) to a level of 900 Gfl (at 1990 prices) in 2020.

Human-induced subsidence is present in The Netherlands due to water-management measures (water level control) and gas mining. The effects of water management have been quite substantial, but mostly pertain to the elevation of inland areas that are already below present mean sea level. Gas mining has a limited and local effect. Therefore, human-induced subsidence was not explicitly considered in this case study.

PHYSICAL CHANGES, SYSTEM RESPONSES AND RESPONSE STRATEGIES

PHYSICAL CHANGES AND NATURAL SYSTEM RESPONSES

All of the relevant physical changes and natural system responses are included in the modeling concept developed for The Netherlands case study. The assessment of these changes and responses takes place according to the following steps:

1. For each geographical area, a resulting flood-level distribution curve is determined. This curve expresses the maximum flood levels as a function of probability, based on the various hydraulic condition zones and protection sections surrounding the geographical area. Note that if a flood-protection system is present, the flood-level distribution curve is only relevant for probabilities equal to or below the probability for which the weakest part of the flood-protection system is assumed to have failed. Clearly, this curve changes due to the effects of sea level rise, increasing flood levels, and flooding probabilities if no protective measures are taken.

2. The flood-level distribution curve (including the effect of tide) as it is changed because of the effect of sea level rise is confronted with each of the subareas in the geographical area. Based on the elevation-distribution of the subarea, it is determined which parts of the subarea now fall within the various land/water categories: dry land, wet land, intertidal, or shallow water. In addition, the dry land part of each subarea is further partitioned into a number of flood-risk classes, all of which are associated with a specific flooding probability.

3. Predefined socioeconomic and ecological values are attributed to the parts of the subareas within the different land/water categories. If parts of the dry land category are shifted to wet land and further to intertidal or shallow water, socioeconomic values are generally lost, and ecological values may be lost or gained.

4. Socioeconomic values within the different risk classes of the dry land category are multiplied by their flooding probability to reflect socioeconomic values at risk. If flooding probability increases, the values at risk will increase.

5. Socioeconomic values lost or at risk and ecological values lost or changed are added up across the subareas in the geographical area to produce a report of the geographical area situation, and are added up across the geographical area to produce an overall vulnerability table.

6. Effects of changes in water quantity (drainage problems) and quality (salinity) are determined for each geographical area separately, and are confronted with the types of land use that may be vulnerable to such changes. Due to the uncertainties involved, no actual damage calculations take place. Potential drainage and salinity problems are translated into certain "values at change," which are added to the vulnerability table.

In the computations according to the above procedure, the following physical effects and phenomena were taken into account:

- The autonomous development of the dune coast for different sea level rise scenarios.
- The effect of increased wave action due to increased water depth (because of sea level rise) on the failure of dikes.
- The effect of sea level rise on morphological processes within hydraulic condition zones. This is expressed by a factor that indicates the extent to which the water bottom follows sea level rise.
- The effect of sea level rise on required pumping capacity for the drainage and water discharge of land areas.
- The effect of sea level rise on the salt load of surface-water and ground-water bodies due to the increase of saline seepage.

An increase of saltwater intrusion in the parts of the lower river system that are openly connected to the sea is not expected, because it is assumed that the riverbed is able to keep up with accelerated sea level rise so that no increase of water depth (which would increase saltwater intrusion) occurs.

Quantitative estimates for these effects and phenomena were derived from existing, more detailed studies and model results that will not be further described in this paper. (More details can be found in Delft Hydraulics, 1991.)

IDENTIFICATION AND SPECIFICATION OF RESPONSE STRATEGIES

The following measures were considered for The Netherlands case study:

- Protection:
    - Dike raising;
    - Dune maintenance and nourishment; and
    - Raising of high-value (harbor/industrial), flood-prone areas (outside the flood-protection system).
- Accommodation:
    - Maintaining the level of Lake IJssel and Lake Marken by installing a water-discharge facility (large capacity sluices or pumping station) to improve the drainage conditions of the adjacent lands and to avoid the cost of dike raising for the protection of land areas surrounding the lakes;
    - Increasing pumping capacity for drainage and water discharge from the land to meet the additional capacity requirements brought about by sea level rise; and
    - Doubling of the present amounts of flushing for all areas that are affected by (increased) saline seepage.

Relevant response strategies to be considered for The Netherlands are:

- *Zero Option*—A situation without measures (doing nothing), to be used as a reference situation.

- *Protect Option 1 (PRO1)*—The full set of protection measures, as mentioned above.

- *Protect Option 2 (PRO2)*—As Protect Option 1, including the measure to maintain the level of Lake IJssel and Lake Marken. This will eliminate the need for dike raising along the lake borders and, hence, can be considered as an alternative protection option.

- *Protect 2 + Accommodate Option (PRO2/AC)*—Protect Option 2, including the remaining water-management measures—i.e., increasing pumping capacity for drainage and water discharge to meet the additional requirements and doubling of flushing of salt-susceptible areas.

VULNERABILITY ANALYSIS MODEL STRUCTURE

The model used for the vulnerability assessment (VA) includes a central processing unit to execute the steps outlined above for the various boundary and scenario conditions, and response strategies, considered. The output generated is stored in a Basic Output Table from which the information can be visualized on the level of individual geographical areas. This part is taken care of by a separate post-processing and presentation module. The latter module also takes care of the generation of the aggregated VA table (for the whole impact area) for the situation considered. The following provides an overview of the contents of this VA table.

Values at Loss
Capital Value at Loss (Gfl)
Subsistence Value at Loss (K#people)

Values at Risk
Capital Value at Risk (Gfl/yr)
Subsistence Value at Risk (K#people/yr)
People at Risk (K#people/yr)

Values at Change
Domestic and Industrial Water Extraction (Mm/yr)
Weighted Average Salinity of Domestic and Industrial Water Extraction (ppm)
Area Horticulture Glass (ha)
Weighted Average Salinity Horticulture Glass (ppm)
Area Arable Land (ha)
Weighted Average Salinity Arable Land (ppm)
Required Drainage Capacity (Mm^3/yr)

Ecological Values at Loss
Nature Area Dry (ha)
Nature Area Wet (ha)
Nature Area Intertidal (ha)
Nature Area Shallow Water (ha)

Cost of Response Strategy
Cost of Response Strategy Cumulative (Mfl)
Cost of Response Strategy Annual (Mfl/yr)

VULNERABILITY ANALYSIS

IMPACTS ON SOCIOECONOMIC AND ECOLOGICAL SYSTEMS

In the actual vulnerability analysis, a number of different "cases" are considered. Such cases consist of a combination of:

- SLR scenario: cm/100 year
- Time horizon considered (from 0 to 100 year)
- Development scenario: Present or Future
- Response strategy: ZERO, PRO1, PRO2 or PRO2/AC

The illustrative analysis is based on the following cases.

	ASLR (cm/100 yr)	T (yr)	Scenario	Strategy
Reference Cases				
Case 00	0	0	Present	ZERO
Case 01	100	30	Present	ZERO
Case 02	100	100	Present	ZERO
Case 03	100	100	Future	ZERO
Strategies/Present				
Case 11	100	100	Present	PRO1
Case 12	100	100	Present	PRO2
Case 13	100	100	Present	PRO2/AC
Strategies/Future				
Case 21	100	100	Future	PRO1
Case 22	100	100	Future	PRO2
Case 23	100	100	Future	PRO2/AC

Tables 5 through 7 show the impacts for the various groups of cases. The following observations should be read carefully when reviewing the tables.

Observations on Table 5

- In the present situation (Case 00), by definition, no losses occur. Capital values at risk and people at risk are small (note that the unit for capital value at risk is 10^9 fl/yr and for people at risk 10^3 people/yr). The capital value at risk results from the multiplication of a large capital value (about 2500 Gfl) with a very small probability of flooding (in the present situation less than $2*10^{-4}$ on average). The people at risk value results from the multiplication of some 10^7 people and a very small probability that on average is even somewhat smaller than for the capital values, indicating that the highest population densities occur in the currently safest areas. One of the reasons for these small differences in present safety between capital and people is that some of the capital value (related to harbor/industrial area) is in areas outside the flood-protection system, while people are not.

- The average salinities shown are weighted across geographical areas according to various uses that might be vulnerable to the effects of salinity (i.e., Domestic and Industrial Water Extraction, Horticulture Glass Area, and Arable Land Area). The Arable Land seems to be in the most unfavorable locations with respect to salinity (Case 00). The weighted-average salinities observed indicate already existing problems in the present situation. However, it should be noted that in a country that has always been subject to saline seepage and salinity intrusion, this situation has already been accommodated. Drinking water is only extracted in the most appropriate (least saline) places. Greenhouse Horticulture has become more or less independent from direct surface- or ground-water extractions, and arable crops are relatively insensitive to salinity because of the very limited irrigation. Therefore, the average salinities shown are not really representative in this respect. However, from the changes of these salinities, an indication can be obtained of the possible increase of the salinity limitations brought about by sea level rise.

- An ASLR of 30 cm (Case 01), resulting from an ASLR scenario of 100 cm/yr after 30 years, already causes the loss of a quite substantial capital value if no measures are taken. This is mainly due to a complete loss of safety in GA14 (part of the province of Zeeland) because of the deterioration of the natural dune protection. This loss occurs because under the Zero Option the assumption is that no protection or maintenance of dunes takes place, which means that most of this effect should be attributed to the autonomous development of the local dune coast, rather than to the impact of sea level rise.

- With the ASLR of 30 cm (Case 01), values at risk increase substantially. Looking at values at change, the salinity changes are quite modest. Note that the dry land areas of Horticulture Glass and Arable Land have somewhat decreased because of the loss of a part of Zeeland. The loss of dry land also becomes visible in the loss of dry land ecological values (which only apply to a limited part of the dry land area) and especially in the increase of wet and shallow water area. The overall effect on intertidal area seems to result in a net loss. (Note that losses are positive and increases of areas are negative.)

- An ASLR of 100 cm (Case 02) under the Zero Option seems disastrous, considering the amounts of capital lost and the increase of the values at risk. Values at change are not so shocking, although a more or less substantial increase of the salinity can be observed for Domestic and Industrial Water Extraction and Arable Land. Because of the losses of dry area, the total areas of Horticulture Glass and Arable Land have now decreased considerably compared to Case 00. These area losses affect the computation of the weighted-average salinities for these areas. In the case of Horticulture Glass, the salinity even goes down, apparently because the Horticulture Glass areas lost were relatively saline. The increase in drainage capacity demand follows to a limited extent from an increase of the amounts of drainage water because of increased seepage, but mostly from the increase in head difference that must be overcome due to sea level rise (compare Case 02 with case 00). The additional drainage requirement would probably lead to severe drainage problems if it were not compensated by additional pumping capacity (which is the assumption in this case). Losses of dry land area are now quite substantial, which can be inferred from the net increases of wet land, intertidal, and shallow water areas. It should be noted that there is no closed balance of the changes in ecological areas. For the wet land, intertidal, and shallow water categories, *all* of the area is considered of ecological value, but for the dry land category, this applies to only a limited part. So there can be an increase of wet land ecological value because of the loss of dry land that has no ecological value. The observed shifts of areas from dryland to wet land and onward to intertidal and shallow water areas might be somewhat misleading. These area shifts follow from the hypothetical situation that valuable protected dry land would be given up. Protected dry land is then allocated to other land/water categories according to the flooding frequency of the (remaining) protection, rather than on the basis of the actual elevation of the land. If protected land at low elevation (below sea level) would really be flooded several times a year in case no measures are taken, it is likely to remain submerged permanently. In other words, the allocation of former dry land to other land/water categories is rather uncertain, and the numbers shown in the table probably largely overestimate the increase in wet land. Further model refinements would be required to correctly represent these phenomena. The general trend shown is correct, however, and the Zero Option can be expected to substantially increase the ecological values associated with wet land, intertidal, and shallow water areas.

- Under the future scenario (Case 03), not surprisingly, the losses and values at risk, as shown in Case 2, substantially increase due to the increased capital values and the number of people. Also the water extractions and areas potentially subject to salinity problems have increased, leading to some minor changes in the computed average salinities. Losses of dry land ecological values have gone up because of the assumed increase of dry land nature area under the future scenario.

Observations on Table 6

- In Table 6, in addition to the cases 00 and 02, the cases 11, 12, and 13 are added for comparison of the effects of the various response strategies. All three strategies have the full Protect Option, which means that capital values at loss are almost prevented (except for the losses associated with the wet land and intertidal areas), and values at risk remain unchanged, as compared to Case 00.

- The Protect Option has a negative effect on wet land and intertidal areas, which can be observed from the ecological areas at loss. Clearly, this follows from the fact that losses of these areas are no longer compensated by the losses of dry land, which will increase the wet land and intertidal areas. The shallow water area increases (Cases 11, 12, and 13).

- The total cost of Protect Option 1 (PRO1) (Case 11) is 23.2 Gfl, leading to an average annual cost of 232 Mfl. The cost of this response strategy only includes the *additional* cost of dike raising, as well as the costs of raising flood-prone areas and dune protection. The cost of regular dike maintenance is not included in this figure. The response strategy cost is reduced under Protect Option 2 (PRO2) (Case 12), where the dike raising along Lake IJssel and Lake Marken is avoided by maintaining the lake levels through the installation of a large pumping station. Note that the cost of this pumping station is more than compensated by the reduction in the total cost of dike raising (compare Cases 11 and 12). Also the required drainage capacity will be reduced if lake levels can be kept at their present values, which follows from the comparison of drainage capacity demand across Cases 11 and 12. The effect on salinity of strategies PRO1 and PRO2 only follows from the fact that area losses are prevented, which influences the computation of the weighted-average salinities; salinities become higher for Horticulture Glass and Arable Land as the most saline areas are no longer lost (compare Cases 11 and 12 with Case 02).

- Introduction of the water-management measure "double flushing" under Strategy PRO2/AC (Case 13) somewhat increases the required drainage capacity. The average salinity reductions are very small, however (compare Cases 12 and 13). Under Strategy PRO2/AC it is assumed that the required additional pumping capacity for the drainage of land areas will be actually installed. This explains the increase in the response strategy cost. The additional drainage capacity raises the cumulative cost of the strategy by 1100 Mfl and the annual cost (at T = 100) by 21 Mfl.

Observations on Table 7

- Table 7 essentially shows the same impacts as Table 6, but not for the future scenario. This boils down to the fact that losses and values at risk prevented by the various strategies are larger, which will make the implementation of such measures even more worthwhile.

TABLE 5. IMPACTS FOR DIFFERENT ASLR AND DEVELOPMENT SCENARIOS

CASE	00	01	02	03
ASLR Scenario	0	100	100	100
Time	0	30	100	100
Development Scenario	Present	Present	Present	Future
Response Strategy	Zero	Zero	Zero	Zero
VALUES AT LOSS				
Capital value (Gfl)		45.5	344.5	482.3
Subsist. value (K#people)		0.0	0.0	0.0
VALUES AT RISK				
Capital value (Gfl/yr)	0.4	8.2	340.0	507.5
Subsist. value (K#people/yr)	0.0	0.0	0.0	0.0
People (K#people/yr)	1.2	189.7	3,573.0	4,287.6
VALUES AT CHANGE				
Dom.+ind.water extraction (Mm^3/yr)	539	539	539	809
Salinity (ppm)	320	355	428	430
Horticulture glass				
Area (ha)	8,640	8,628	7,514	9,016
Salinity (ppm)	327	335	318	318
Arable land				
Area (ha)	592,350	543,430	463,371	380,698
Salinity (ppm)	618	619	756	751
* Drainage capacity Demand (Mm^3/yr)	5,906	6,674	8,741	8,741
ECOLOGICAL VALUES AT LOSS				
Area dry land (ha)		7,710	86,400	116,600
Area wet land (ha)		-69,980	-241,200	-241,200
Area intertidal (ha)		5,290	-44,230	-44,230
Area shallow water (ha)		-14,200	-83,300	-83,300
COST RESPONSE STRATEGY				
Cumulative (Mfl)		0	0	0
Annual (Mfl/yr)		0	0	0

TABLE 6. IMPACTS OF DIFFERENT RESPONSE STRATEGIES FOR THE PRESENT SCENARIO

CASE	**00**	**02**	**11**	**12**	**13**
ASLR Scenario	**0**	**100**	**100**	**100**	**100**
Time	**0**	**100**	**100**	**100**	**100**
Development Scenario	**Present**	**Present**	**Present**	**Present**	**Present**
Response Strategy	**Zero**	**Zero**	**PRO1**	**PRO2**	**PRO2/AC**
VALUES AT LOSS					
Capital value (Gfl)		344.5	0.8	0.8	0.8
Subsist. value (K#people)		0.0	0.0	0.0	0.0
VALUES AT RISK					
Capital value (Gfl/yr)	0.4	340.0	0.4	0.4	0.4
Subsist. value (K#people/yr)	0.0	0.0	0.0	0.0	0.0
People (K#people/yr)	1.2	3,573.0	1.2	1.2	1.2
VALUES AT CHANGE					
Dom.+ind. water extraction (Mm^3/yr)	539	539	539	539	539
Salinity (ppm)	320	428	428	430	410
Horticulture glass Area (ha)	8,640	7,514	8,640	8,640	8,640
Salinity (ppm)	327	318	359	359	352
Arable Land Area (ha)	592,350	463,371	592,350	592,350	592,350
Salinity (ppm)	618	756	848	848	817
Drainage capacity Demand (Mm^3/yr)	5,906	8,741	8,741	8,474	8,757
ECOLOGICAL VALUES AT LOSS					
Area dry land (ha)		86,370	0	0	0
Area wet land (ha)		-241,200	30,050	30,050	30,050
Area intertidal (ha)		-44,230	34,200	34,200	34,200
Area shallow water (ha)		-83,300	-67,800	-67,800	-67,800
COST RESPONSE STRATEGY					
Cumulative (Mfl)			23,162	21,630	22,730
Annual (Mfl/yr)			232	216	237

TABLE 7. IMPACTS OF DIFFERENT RESPONSE STRATEGIES FOR THE FUTURE SCENARIO

CASE	00	03	21	22	23
ASLR Scenario	0	100	100	100	100
Time	0	100	100	100	100
Development Scenario	Future	Future	Future	Future	Future
Response Strategy	Zero	Zero	PRO1	PRO2	PRO2/AC
VALUES AT LOSS					
Capital value (Gfl)		482.3	0.8	0.8	0.8
Subsist. value (K#people)		0.0	0.0	0.0	0.0
VALUES AT RISK					
Capital value (Gfl/yr)	0.7	507.5	0.7	0.7	0.7
Subsist. value (K#people/yr)	0.0	0.0	0.0	0.0	0.0
People (K#people/yr)	1.5	4,288.6	1.5	1.5	1.5
VALUES AT CHANGE					
Dom.+ind. water extraction (Mm^3/yr)	809	809	809	809	809
Salinity (ppm)	321	430	430	432	411
Horticulture glass area (ha)	10,367	90,16	10,367	10,367	10,367
Salinity (ppm)	327	318	359	359	352
Arable land area (ha)	483,881	380,698	483,881	483,881	483,881
Salinity (ppm)	617	751	842	842	812
Drainage capacity Demand (Mm^3/yr)	5,906	8,741	8,741	8,474	8,757
ECOLOGICAL VALUES AT LOSS					
Area dry land (ha)		116,600	0	0	0
Area wet land (ha)		-241,200	30,050	30,050	30,050
Area intertidal (ha)		-44,230	34,200	34,200	34,200
Area shallow water (ha)		-83,300	-67,800	-67,800	-67,800
COST RESPONSE STRATEGY					
Cumulative (Mfl)			23,162	21,630	22,730
Annual (Mfl/yr)			232	216	237

INSTITUTIONAL IMPLICATIONS OF RESPONSE STRATEGIES

In the common methodology (IPCC, 1991), a checklist containing a great many implementation aspects was suggested to be considered in the judgment of the vulnerability with respect to the implementation feasibility of response strategies. These aspects were structured according to the following categories:

1. Legislative/Institutional/Organizational (VA-LIO)
2. EConomical/Financial (VA-ECF)
3. TEChnical (VA-TEC)
4. Cultural/SOcial (VA-CSO)

Within those categories, different problem levels are distinguished as follows:

- Level A: Problems related to the (non-)existence of basic institutions and requirements.
- Level B: Problems related to operational and implementation aspects;
- Level C: Problems related to quality and functionality (effectiveness).

Furthermore it was suggested to indicate for each of the items in the checklist whether a problem, no problem, or a partial problem is to be expected. Going through this procedure for The Netherlands, it turns out that only a few very limited problems might be expected in relation to the implementation of the response strategies considered.

In general, the legislative/institutional/organizational structures are very well developed and operational within The Netherlands, so no problems are to be expected within this category.

The same conclusion holds for the economic/financial category, which can be illustrated as follows. The most essential implementation aspect in this category relates to the finance potential. Comparing the maximum annual response strategy cost of 237 Mfl with the present gross domestic product of 500 Gfl (less than 0.5 percent) indicates there should not be a problem. This conclusion is even stronger if the maximum annual costs are compared to a possible future GDP on the order of 900 Gfl. It should be noted that the cost of the strategy does *not* include the cost of regular dike maintenance. The regular annual dike maintenance cost for the whole of The Netherlands currently amounts to about two times the maximum annual response strategy cost.

A first partial problem arises within Level B of the technical category, in relation to the operational structures and procedures for the implementation of technical works. The experience is that present procedures are very time consuming. This means that the total preparation and implementation time might provide a bottleneck for the timely realization of the necessary measures. Ironically, this potential time problem is partly due to the very existence of the well-developed legislative, institutional, and organizational structures. Since procedures can be changed if an urgent need arises, this should not be considered a very serious problem.

A second potential problem might arise in the cultural/social category. This relates to the long history of The Netherlands in dealing with land reclamation, flooding, salinity, and drainage problems. The fact that these problems have been very well controlled for a long time has somewhat reduced the awareness and acceptance of the people in relation to the ongoing need of maintaining and adjusting the infrastructural facilities to keep these problems under control. In fact, one could say that in the absence of problems that are actually felt, the willingness to make sacrifices to maintain this favorable situation gradually decreases. This phenomenon might pose some small problems when decisions are to be made about more or less substantial investments in relation to the impacts of sea level rise.

INTERPRETATION AND EVALUATION

For a further interpretation of the results in Tables 5, 6 and 7, impact categories will be classified in the vulnerability classes Low, Medium, and High, according to Table 8.

TABLE 8. SPECIFICATION OF VULNERABILITY CLASSES

Impact Category	Vulnerability Classes		
	Low	Medium	High
Values at loss			
(Capital value loss/total cap. investment) * 100%	< 0.1%	0.1%-1%	> 1%
Values at risk	< 0.1%	0.1%-1%	> 1%
(Capital value risk/total cap. investment) * 100%	< 10	10-1,000	> 1,000
People at risk			
Values at change	< 10%	10%-50%	> 50%
Change of salinity dom.+ind. water extraction	< 10%	10%-50%	> 50%
Change of salinity Horticulture Glass	< 10%	10%-50%	> 50%
Change of salinity Arable Land	< 10%	10%-50%	> 50%
Drainage capacity shortfall			
Ecological values at loss	< 3%	3%-15%	> 15%
(nature area dry lost/total dry nature area) * 100%	< 3%	3%-15%	> 15%
(wet land area lost/total wet land area) * 100%	< 3%	3%-15%	> 15%
(intert. area lost/total intert. area) * 100%	< 3%	3%-15%	> 15%
(shall.w. area lost/total shall.w. area) * 100%			

For The Netherlands case study the relevant scaling factors are:

	Development Scenario	
	Present	*Future*
Total capital investment (Gfl)	4,200	6,150
Total dry nature area (ha)	373,000	546,000
Total wet land area (ha)	44,000	44,000
Total intertidal area (ha)	138,300	138,300
Total shallow water area (ha)	271,500	271,500

Tables 9 and 10 show the vulnerability for the various cases considered according to the vulnerability classes as defined in Table 8.

TABLE 9. VULNERABILITY FOR ZERO STRATEGY CASES

Case Impact Category	01	02	03
Values at loss			
1 Capital Value	HIG	HIG	HIG
Values at risk			
2 Capital Value	MED	HIG	HIG
3 People	MED	HIG	HIG
Values at change			
4 Salinity dom.+ind water extraction	MED	MED	MED
5 Salinity Horticulture Glass	LOW	LOW	LOW
6 Salinity Arable Land	LOW	MED	MED
7 Drainage capacity shortfall	MED	MED	MED
Ecological values at loss			
8 Nature area dry	LOW	HIG	HIG
9 Wet land area	POS	POS	POS
10 Intertidal area	MED	POS	POS
11 Shallow-water area	POS	POS	POS

For case description see Table 5.

TABLE 10. VULNERABILITY FOR DIFFERENT RESPONSE STRATEGIES AND DEVELOPMENT SCENARIOS

Case Impact Category	11/21	12/22	13/23
Values at loss			
1 Capital Value	LOW	LOW	LOW
Values at risk			
2 Capital Value	LOW	LOW	LOW
3 People	LOW	LOW	LOW
Values at change			
4 Salinity dom.+ind water extraction	MED	MED	MED
5 Salinity Horticulture Glass	LOW	LOW	LOW
6 Salinity Arable Land	MED	MED	MED
7 Drainage capacity shortfall	MED	MED	LOW
Ecological values at loss			
8 Nature area dry	LOW	LOW	LOW
9 Wet land area	HIG	HIG	HIG
10 Intertidal area	HIG	HIG	HIG
11 Shallow-water area	POS	POS	POS

For case descriptions, see Tables 6 and 7.

From Tables 9 and 10, the following conclusions can be drawn:

- If no measures are taken, for Cases 02 and 03 (100 cm ASLR, present, and future development scenarios) vulnerability is (very) high for capital value at loss, capital value at risk and people at risk. The vulnerability on some of the salinity aspects might be medium, but as was already mentioned, the actual vulnerability is probably low because of the already existing accommodation in the present situation. There is a medium (close to high) vulnerability for the drainage/discharge capacity shortfall. Different effects occur for ecological values at loss, but the overall effect may well be positive. (In Tables 9 and 10, a positive effect is indicated by POS.)

- The response strategies PRO1 and PRO2 (Cases 11/21 and 12/22 in Table 10) eliminate the vulnerability on capital value at loss, capital value at risk, and people at risk. Strategy PRO2/AC (Cases 13/23 in Table 10) also eliminates the vulnerability on drainage/discharge shortfall. The vulnerability on the salinity aspects (if existing) cannot be taken away by the "double flushing" measure, but the gravity of this vulnerability is questionable because of the possibilities to (further) accommodate.

- The response strategies considered in Table 10 all have a severe impact on the ecological values associated with the wet land and intertidal areas. The vulnerability on these aspects is to be considered high.

With respect to the implementation feasibility, the overall conclusion is that for The Netherlands the resulting vulnerability on all categories of implementation aspects should be considered LOW for all response strategies. The overall conclusion is that the losses of wet land and intertidal areas are the only severe impacts to which The Netherlands is really vulnerable.

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THE IMPACTS OF SEA LEVEL RISE ON THE COASTLINE OF NIGERIA

Larry F. Awosika and C.E. Ibe
Nigerian Institute for Oceanography and Marine Research
Victoria Island, Lagos, Nigeria

Gregory T. French and Robert J. Nicholls
Laboratory for Coastal Research
University of Maryland
College Park, Maryland

ABSTRACT

Much of Nigeria's population and economic activity is located along the country's 853 km of coastline. The Niger delta, the capital city of Lagos, and the country's vital oil industry are all found in the low-lying coastal zone. A 1-meter rise in sea level could flood 18,000 km^2 of land, forcing about 3,680,000 people to relocate, and damaging assets valued currently at $19 billion when the value of oil-producing facilities are factored in. Protecting the country's entire coastline is economically infeasible. Protecting the highly developed coastal areas and oil infrastructure alone would cost $550–650 million (1991 U.S.). Total protection of all moderately developed areas would cost about $1.2 billion. If this investment occurred over 50 years (2050 to 2100), it would represent an annual cost of 0.2 percent of the national gross investment in 1987. In addition, over 600,000 people in the less developed Niger delta and the Mahin mud coast would require relocation, and 17,000 km^2 of wetlands would be lost. Managing the sediment deposited in the Niger delta would help reduce the area's susceptibility to sea level rise.

INTRODUCTION AND BACKGROUND

Nigeria is located along Africa's west-central coast. Its coastline is approximately 853 km long, bounded on the west by the Benin Republic and on the east by Cameroon (Figure 1). Because of the extremely low elevations and slopes of its coastal zone, Nigeria is subject to recurrent flooding both from coastal storms and during the annual rainy season of May through September. An estimated 29 to 35 million people (or 25 to 30 percent of the population) live and work in the coastal zone. Some 85 percent of the country's 2,000 industrial establishments are located there, as is the majority of the country's oil exploration/exploitation facilities.

COASTAL CHARACTERISTICS

The Nigerian coast can be broken into four major shoreline types, or geomorphic units, from west to east: the Barrier/Lagoon Coast (220 km in length), the Mahin Transgressive Mud Coast (83 km), the Niger Delta Coast (450 km), and the Strand Coast (100 km) (Figure 2).

FIGURE 1. THE NIGERIAN COAST

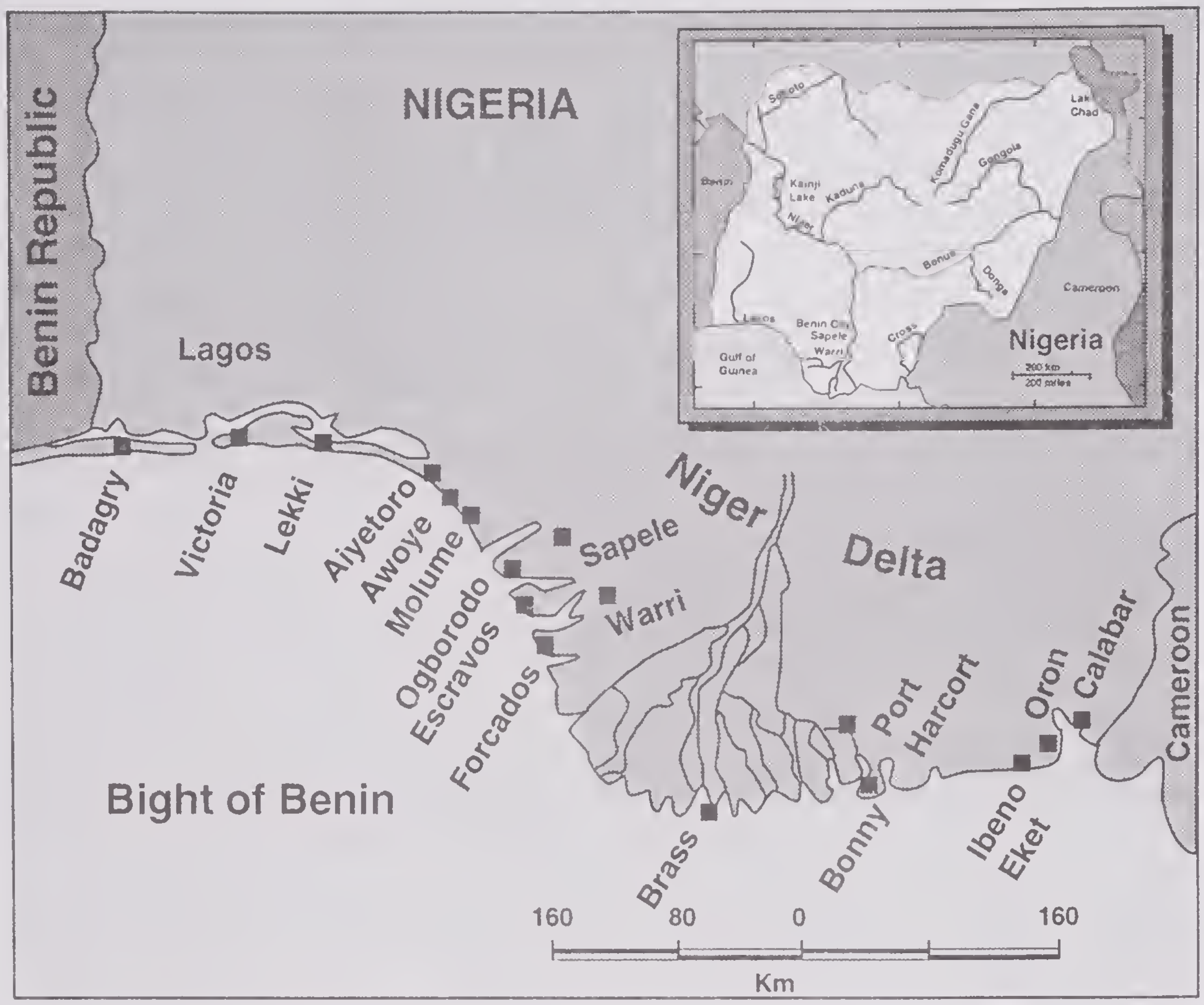
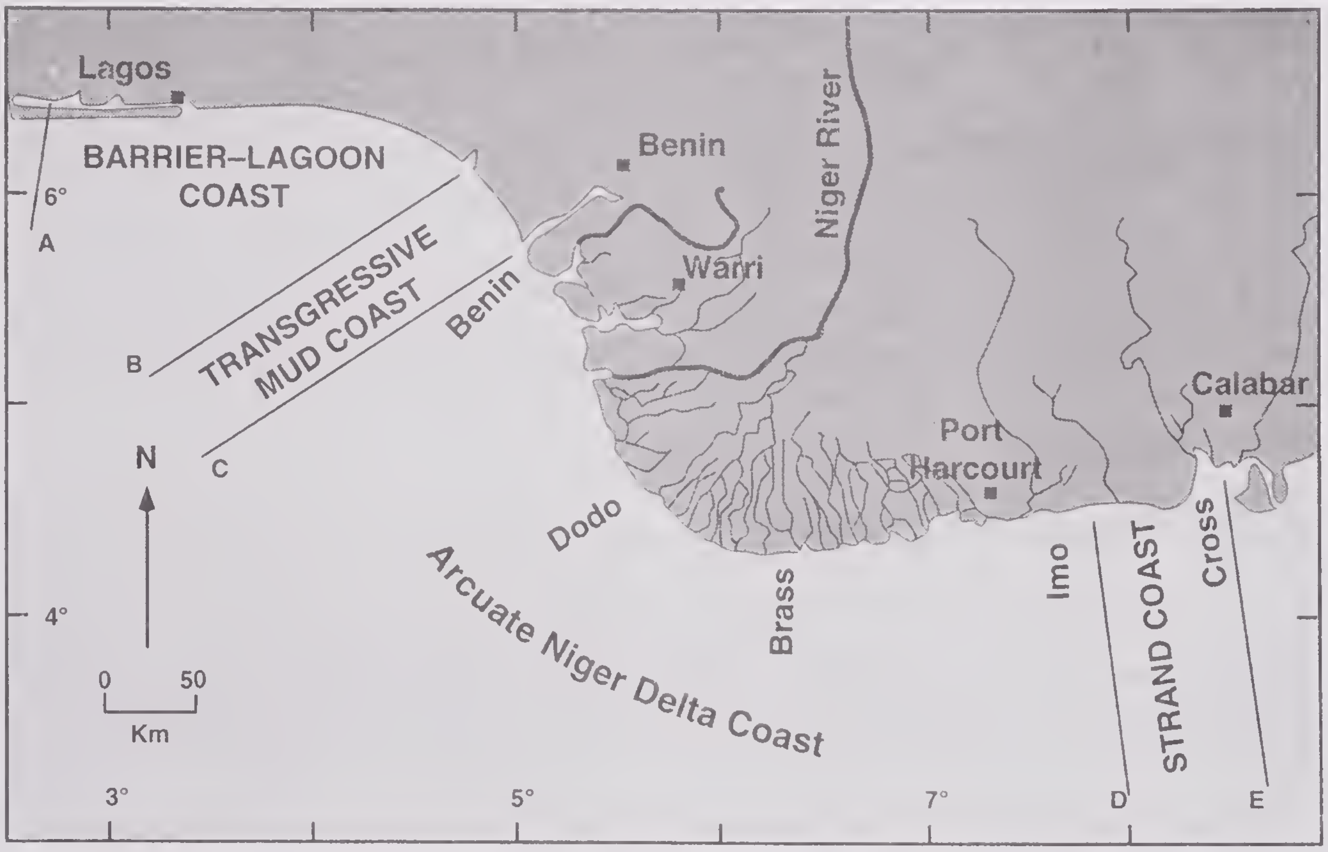


FIGURE 2. NIGERIAN COASTAL GEOMORPHOLOGY



BARRIER/LAGOON COAST

The westernmost coastal type, the sandy Barrier/Lagoon Coast, extends from the Benin/Nigerian border about 200 kilometers east to the westernmost extent of the Mahin Transgressive Mud Coast. This geomorphic unit is characterized by a sandy barrier that varies in width from 0.5 to 21 km and is separated from the mainland by the Badagry Creek, and the large irregularly shaped Lagos and Lekki Lagoons (Ibe and Awosika, 1989).

The coastal barrier island is comprised of a series of narrow beach ridges that are aligned roughly parallel to the present coastline. Intertidal beach profiles are generally steep, averaging 1:6, with narrow beach faces. Dune elevations range from nearly 4 meters at the Nigerian-Benin border, to just under 1 meter at the eastern end of Bar Beach.

The beach sediment is medium to coarse sand (1.43 to 0.05 phi) (Ibe, 1988). Hence, it is large enough to remain in the active profile zone. However, there are low-lying wetlands behind the barrier islands and around the lagoons. If these areas are considered, a larger area is at risk of inundation than erosion on the Barrier/Lagoon Coast.

TRANSGRESSIVE MUD COAST

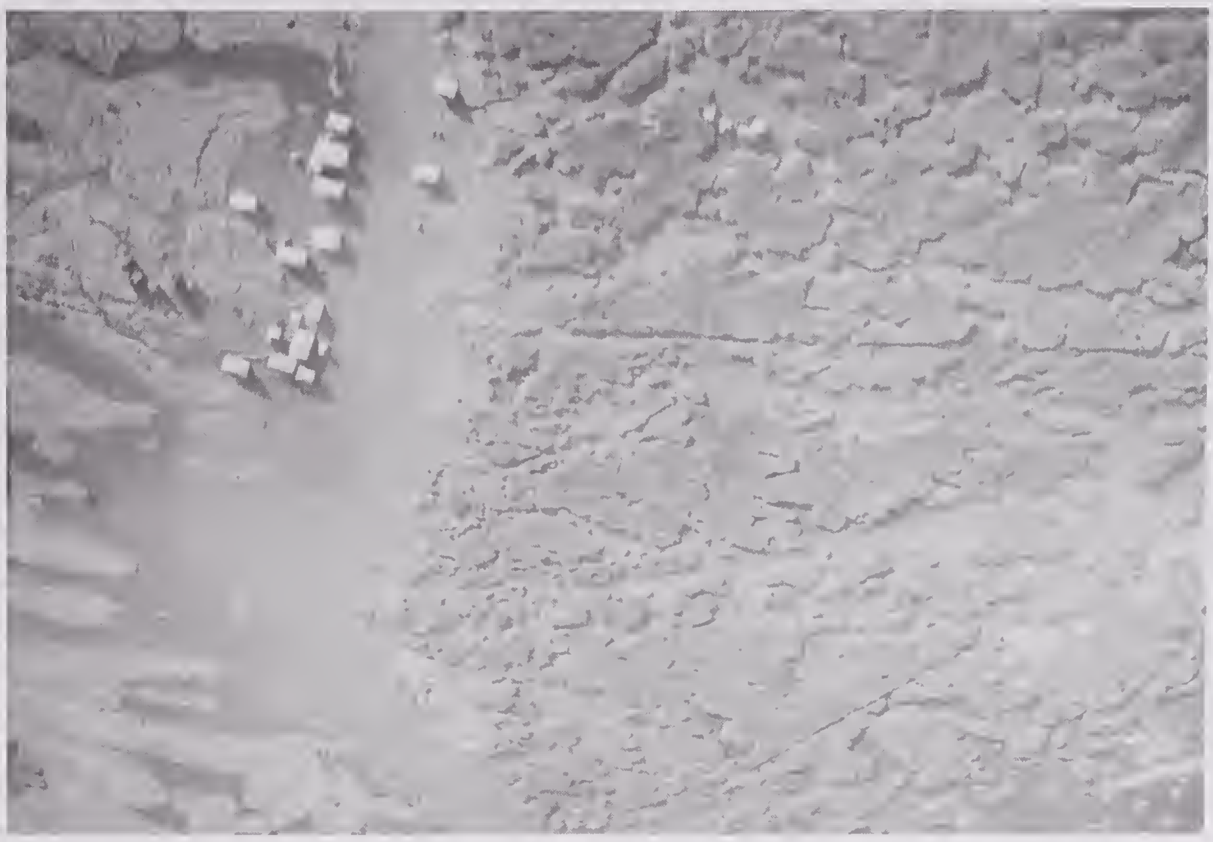
The Transgressive Mud Coast is characterized by medium to coarse silt (6.27 to 4.27 phi), with small quantities of fine to medium sand (3.23 to 1.0 phi). Slopes here are very low. The intertidal zone typically has a slope of 1:50, with a very broad subtidal platform (1-2 km wide). Elevations in the region of the adjacent towns of Awoye/Molume (near the center of this coastal type) are very low, in the range of 0.8 to 1.8 meters above mean sea level (Ibe, 1985, 1987). Spring high tides already reach as high as 1.82 meters, frequently subjecting the area to severe flooding (Figure 3).

Erosion along this coastline is already reportedly very high, being as much as 110 meters/year in some locations (Ibe, 1988). This area receives little or no new sediment supply, either by longshore transport or from fluvial sources. Because of the small sediment sizes, it is believed that much of what is eroded is lost to the system offshore, with very little resupply.

NIGER DELTA COAST

The Niger delta, the largest delta in Africa (Funk & Wagnalls, 1979), is characterized by approximately 20,000 km^2 of mangrove swamps at or very close to present sea level (Ibe and Awosika, 1989). A high proportion of the delta's ocean coast is fronted by a series of 20 barrier islands, characterized by low, narrow sandy beaches where numerous fishing villages are located (Ibe, 1988). The maximum elevation of the beach ridges found on these islands is only 1 to 3 meters above mean high tide, and they are frequently subject to storm-induced overwashing. These islands are separated by a number of tidal channels leading to extensive swampland behind. In some areas, the mangrove swamps extend as much as 50 km inland. None of the mangrove swamps is higher than 2 meters above mean high tide.

FIGURE 3. A SMALL FLOODED INLAND SETTLEMENT ON THE MUD COAST



The marsh is showing possible signs of break-up due to inundation.

The Delta Coast receives relatively little new sediment today, compared with the past. A major factor behind this is the Kainja reservoir some 350 km upstream of Lokoja (central Nigeria) on the Niger River. This is because most of the sediment load that was once transported to the delta is now deposited in the Kainja reservoir on the Niger River (Tilman et al., 1989).

STRAND COAST

The Strand Coast runs about 100 km at the eastern end of the country. It is characterized by moderately wide (75 meters), gently sloping (1:20) beach face that changes into beach ridge plains behind, with a few small swamp systems that extend to the shore (Ibe, 1988). The entire coast is further backed by a relatively narrow strip of mangrove swamps subject to frequent and extensive flooding. Grain sizes range from very fine to fine sand, with the swamps that front the sea composed of interbedded silt and clay.

ANALYTICAL METHODS

This study estimated the land lost due to sea level rise, the economic value of that land, and the cost of protecting it.

SEA LEVEL RISE SCENARIOS

Four arbitrary scenarios of eustatic (or worldwide) sea level rise were used for this study: 0.2 (baseline scenario: no acceleration), 0.5, 1.0, and 2.0 meters by the year 2100. Changes of relative sea level in Nigeria and, in particular, in the delta, could be higher due to enhanced subsidence. However, the data for quantifying this are insufficient. Hence, a constant scenario was used for the entire country.

AERIAL VIDEOTAPE-ASSISTED VULNERABILITY ANALYSIS

One of the major problems with studying the impacts of sea level rise in developing countries is the lack of detailed information on coastal elevations. Maps available in Nigeria have, at best, 30.5-meter contours. Several methods of obtaining the required topographic data were examined. Traditional aerial photography is prohibitively expensive and time consuming, requiring a high density of quality benchmark data that are rare in West Africa. Satellite imagery was also considered, but it is also prohibitively expensive and is not sufficiently accurate for the purposes of this study.

Given these constraints, the strategy was to apply aerial videotape-assisted vulnerability analysis and develop rough estimates of coastal elevations by obliquely videotaping the coastline at low elevations from a light airplane. The full methodology is outlined in Niang et al. (see Senegal in these proceedings), with more complete details in IPCC (1992) and Nicholls et al. (1992). In summary, the video record provides the following information on the coastline: (1) an index of terrain and relief changes, (2) the types of coastal environments, (3) land-use practices, (4) infrastructure, and (5) population indicators.

The entire coastline was flown and videotaped by Awosika and French at the altitudes of approximately 75 and 300 meters. In addition, much of the Lagos and Lekki Lagoons, and the Escravos, Forcados, Bonny, and Cross River Estuary shorelines were videotaped at the lower altitude. It was not possible to videotape the city of Lagos because of air traffic control constraints. Precise positions were recorded approximately every 4 minutes in real time using portable Global Positioning Satellite (GPS) equipment carried on board the aircraft.

FIELDWORK

Because of the low gradient of the Nigerian coastal zone, the land loss impacts of sea level rise will extend inland, beyond the view afforded by the video record. Therefore, supplementary information was essential for this study, particularly Awosika's expert judgment. The total land loss due to sea level rise in Nigeria was estimated by combining all this information with local maps and in-field spot heights, bathymetric charts, and wave data.

Six representative beaches along the entire length of the Barrier/Lagoon Coast were visited by Awosika and French to identify, photograph, and measure prominent features—natural and manmade—that were clearly visible from the air and that could, therefore, be used for scaling purposes when viewing the video record. A survey team from the Nigerian Institute for Oceanography and Marine research visited the Mahin Mud, Delta, and Strand Coasts in helicopters and boats. The team took a series of 14 representative beach profiles along the whole coast, including all four coastal types.

In addition, government agencies were visited to acquire the best maps and the best demographic, economic, and geographic data available. The maps acquired have scales ranging from 1:5,000 (for the Lagos harbor area) to the more typical 1:250,000 and 1:300,000 covering the entire coastline.

LAND-LOSS ESTIMATES

EROSION

The Bruun Rule is much used to estimate erosion due to sea level rise (Bruun, 1962; Leatherman, 1991). The following equation for the Bruun Rule, after Hands (1983), was used in the sandy coast retreat estimates:

$$R = (L/(B+h_*)) * S * G \qquad (1)$$

where:

R is the shoreline recession due to a sea level rise S;
h_* is the depth of closure;
B is the dune height (note $H = h_* + B$)
L is the active profile width from the dune to the depth of closure;
G is the overfill ratio.

The dune height and the beach width (which is part of the active width, L) were estimated from the video record, combined with profile measurements of representative beaches. The depth of closure, h_* was calculated and plotted on bathymetric charts of Nigeria. The active width L was then measured from these charts. The depth of closure in the Bruun Rule equation is the most difficult variable to estimate. Therefore, high and low closure depths were estimated, giving a low and high estimate of retreat (Niang et al., these proceedings). In Nigeria, they were found to be 5.4 meters and 9.4 meters, respectively.

The depth-of-closure contours were referenced to a datum 1 meter above low water at 14 widely spaced stations along the coast. They were then plotted on a series of 1:300,000 and 1:288,500 scale British Admiralty and U.S. Defence Mapping Agency navigation charts. Because of the relative steepness of the Barrier/Lagoon Coast, it was necessary to interpolate the locations of the depth of closure contours from the 6-fathom (10.97 meter) contour (the shallowest bathymetric map contour available). A direct linear interpolation was used to determine the high-estimate depth-of-closure contour. However, because of the concave-up configuration of the near-shore profile, the interpolated values for the offshore distance to the low-estimate depth-of-closure contour was assumed to be 25 percent of the values found for the high estimate.

Plotting the depth-of-closure contours was straightforward for the other three coastline types. The Bruun Rule was considered invalid for the Transgressive Mud Coast because of the preponderance of silt and mud. Therefore, land-loss estimates for that segment of coast are based solely on inundation. Because of the presence of the bounding sandy barrier islands along the Delta Coast, a combination of Bruun Rule and inundation estimations were employed for this section, although the Bruun Rule estimates constituted only a small percentage of the total land lost relative to the land lost due to inundation. The distance from the high and low depth-of-closure contours of each coastline section to their respective shorelines was then measured at 10-km intervals, averaged for each shoreline type, and added to the dry beach widths from the appropriate profiles to produce the total active beach width.

INUNDATION

The available information from topographic maps (normally 30.5-meter contours), limited spot heights, the video record, and, in particular, the expert judgment of Awosika, were compiled to estimate the location of the 2-meter contour relative to mean high water. The assumption that all cartographically indicated marsh and swamp were no higher than 1 meter above mean high water (supported by infrequent spot heights on the maps) was used to delimit the 1-meter contour.

The two contours were plotted on the topographic maps. It was necessary to interpolate the land loss for 0.2 and 0.5 meters of sea level rise, since the information available is not detailed enough to plot the contour for each of the scenarios. Once the 2-meter contour was plotted, the amount of land lost was determined by using a modified-grid matrix method called the percent polygon estimation (PPE) method (Niang et al., these proceedings). Double counting of the erodible barrier island areas was avoided by estimating the total area of barrier island based on descriptions of the islands, maps, and video record, then subtracting that amount from the inundation values. These estimates do not take into account the possibility of sedimentation in the inundated area. However, as previously stated, there is little to no resupply of sediment to either the Mud or the Delta Coast.

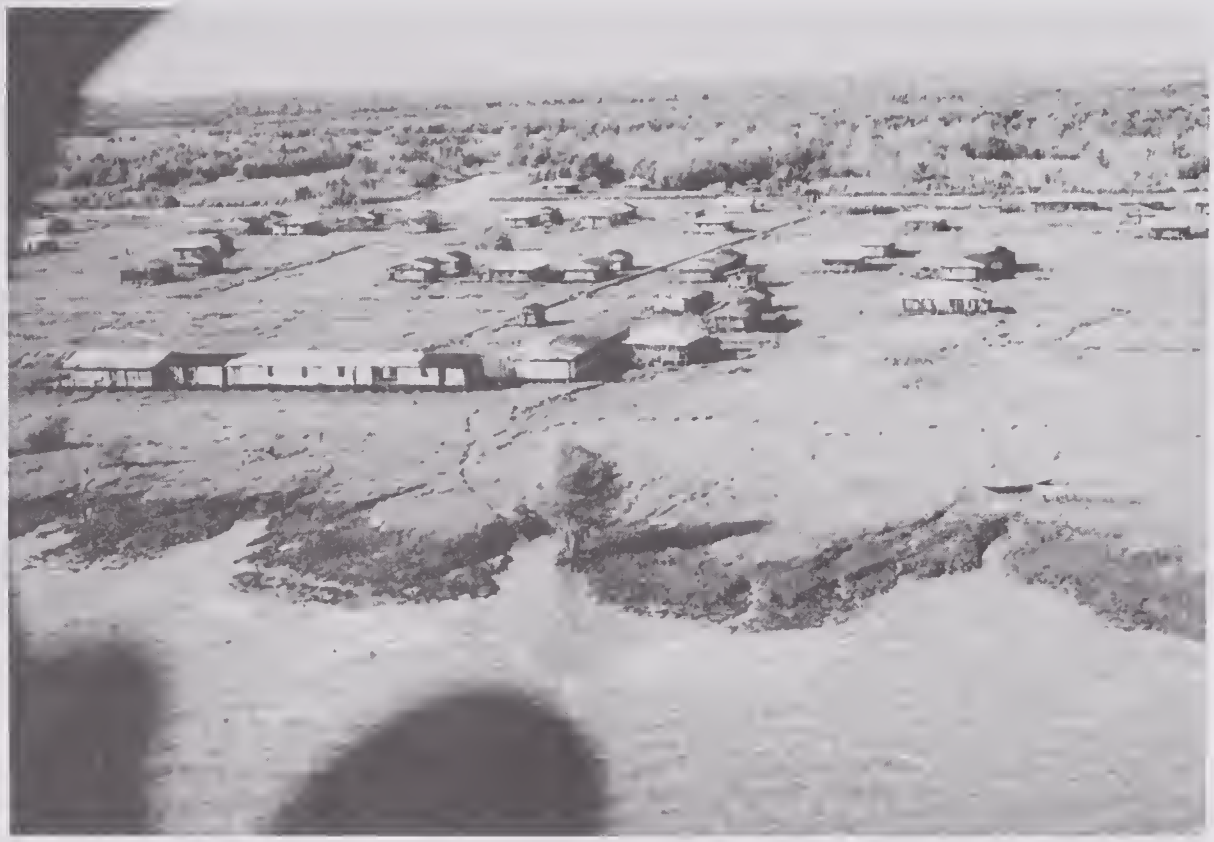
ECONOMIC AND LAND-USE ANALYSES

To estimate the economic value of the land lost, information derived from the video record was analyzed, along with cartographic and in-country demographic and economic data. All estimates of land loss and population displacement assume a no-protection response scenario. The present distribution of population in Nigeria is poorly known, and approximate estimates of population for such areas as greater Lagos were provided by the Nigerian Institute for Oceanography and Marine Research. Estimated property values for different structure types were provided by Lagos insurance underwriters and Awosika.

The population currently living at the 2-meter contour above mean high water is believed to be as high as 10 million. This is not unreasonable, in that it is believed that some 30 million people live within the defined coastal zone, and some estimates place the greater Lagos population at as high as 8 million (Awosika et al., 1989). Because of widely varying estimates of the population in the greater Lagos urban area, an estimate of 5 million was used for the purposes of this study. Nearly all of the Lagos urban area is less than 2 meters above mean high tide, and it was assumed that the entire urban area would be inundated with a 2-meter rise in sea level. The population displacement for lower sea level scenarios was scaled linearly from the 2-meter values.

In the Mud Coast region, potential population displacement for each sea level rise scenario was based on video and cartographically derived village counts. The largest settlements, Aiyetoro and Awoye/Mulome, were assumed to be lost with even a 0.2-meter rise in sea level, because of the existing flooding problems that result from their extremely low elevation and proximity to the sea (see Figures 3 and 4). As previously stated, the village counts for the Mud, Delta, and Strand Coasts are believed to be low because of inadequacies in the data available.

FIGURE 4. TYPICAL VILLAGE CLOSE TO THE RAPIDLY ERODING MUD COAST



The same technique was employed for the Delta and Strand Coasts. In the Delta, three cities (Degema, Yenagoa, and Warri) are located between the interpolated 1-meter (above mean high water) and 2-meter (above mean high water) contours, so they are only threatened with the 2-meter sea level rise scenario. Therefore, there is a significant jump in the cost/displacement figures between the 1- and 2-meter scenarios.

Very little of the immediate coastal zone near the sea is fit for agriculture. This is largely due to the high salinization of the soil and aquifer as well as the many areas subject to frequent seasonal flooding (Awosika et al., 1989). Therefore, the loss of agricultural land was not a consideration for this study.

The number of people who would be displaced by the various sea level rise scenarios was also estimated. The number of people per house was assumed to range from 7 to 20. This number is reasonable, since several generations of the family live together, and often, as in the bungalows, several families share a communal central living area. It was further assumed that, within the urban areas, approximately 60 percent of the population would live in four-family flats, 30 percent in bungalows, 5 percent in wood structures, 3 percent in high-rise apartments, and 1 percent in the very expensive single-family houses. In the rural areas, it was determined from a 100-village sample (taken from the video) that, on average, 30 percent of the population live in wood/mud structures, and 70 percent live in block structures.

ESTIMATED COSTS OF PROTECTION

Three protection options were considered:

1. *No protection.* Assumes no protection (any protection that already exists is not taken into consideration).

2. *Important-areas protection.* All important areas with medium to high development will be fully protected (e.g., cities, tourist beaches, factories, oil facilities).

3. *Total protection.* All areas along the coast with populations greater than 10 inhabitants/km^2 will be protected. This is the same assumption as made in a study of the worldwide cost of a 1-meter sea level rise by the IPCC (1990).

Other studies have also considered existing protection (Niang et al., these proceedings). However, in the case of Nigeria, it proved impossible to acquire a comprehensive accounting of all present protection projects. For instance, due to the vastness of the Niger delta, the video record was insufficient to provide a complete inventory. Therefore, because of these constraints, no attempt was made to estimate costs of maintaining protection of shorelines currently protected. Existing protection is, nevertheless, significant. Gross estimates place the current and planned expenses at perhaps as high as U.S. $500 million (Onalaja, 1991).

SEA WALL AND NOURISHMENT DESIGN

Two principal coastal engineering techniques were considered for the Nigerian Coast: sea walls and beach nourishment. The full methodologies employed in the estimations are detailed in Niang et al. (these proceedings). Costs per cubic meter of the nourishment protection structures were set at U.S. $100. The cost estimation was based on calculated costs for materials transport and placement from the Nigerian Federal Ministry of Works & Housing, Flood & Erosion Control Division, Lagos (Onalaja, 1991). Design costs (10 percent) and maintenance costs (20 percent) were added to the cost of the protection structures to determine total structure cost. For beach fill (sand), estimated costs per cubic meter ($10/m^3) were obtained from the same source.

To calculate the cost of erecting a sea wall, three simple sea wall designs were created (Niang et al, these proceedings). The three designs are basically a low and a high estimate of the cost of protecting against sea level rise using a sea wall on the open (or wave-exposed) coast and a design for a sheltered coast. The costs for each sea wall scenario per kilometer of shoreline in Nigeria are listed in Table 1.

TABLE 1. SEA WALL COSTS PER KILOMETER (MILLIONS OF U.S. DOLLARS)

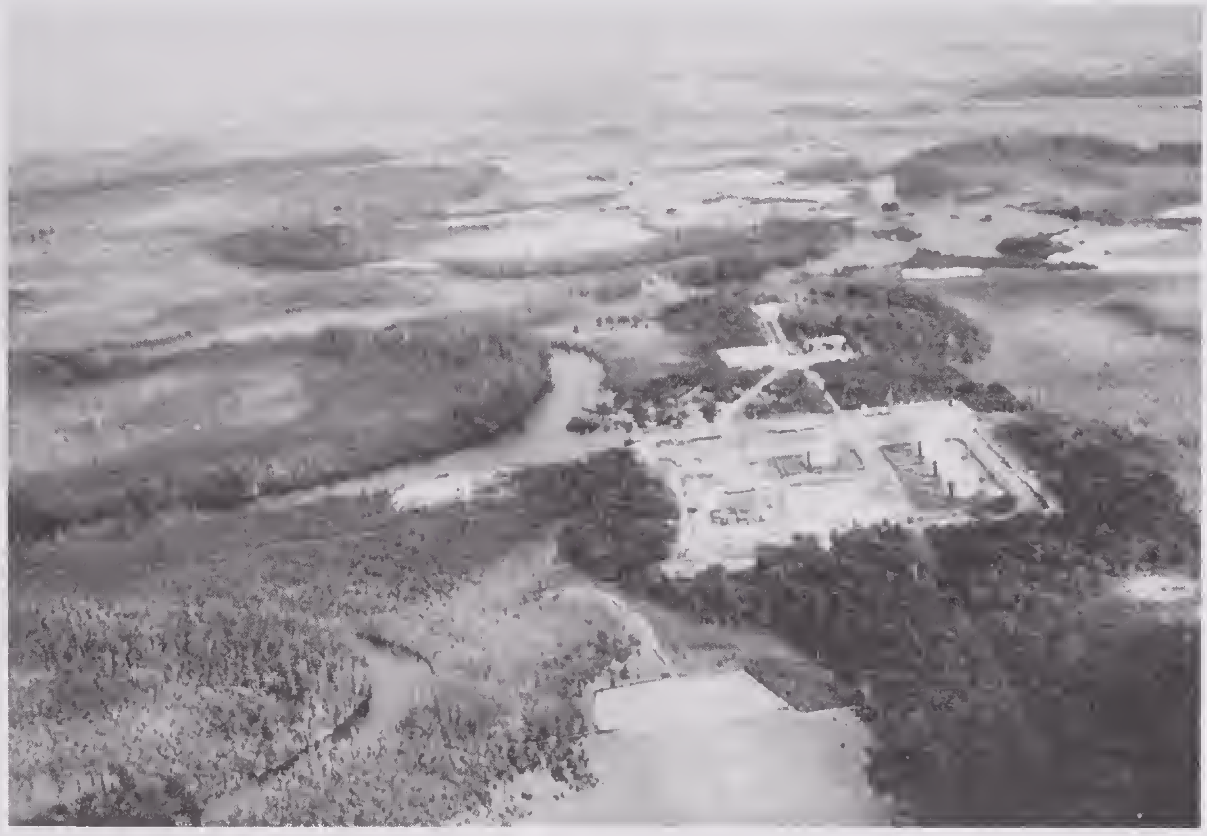
Area Protected		**Sea Level Rise Scenarios**		
	0.2 m	*0.5 m*	*1.0 m*	*2.0 m*
Sheltered	$0.06	$0.16	$0.52	$1.56
Open Coast	$0.08 - 0.99	$0.25 - 1.27	$0.69 - 1.86	$2.12- 3.42

OIL PRODUCTION

An additional, and significant, cost will be for the protection of the numerous oil extraction and processing facilities scattered throughout the delta (Figure 5). Within the threatened areas of the delta are some 259 producing oil fields with an average of 5 wells each, resulting in a total of 1,300 individual well heads that will require protection. (Obviously, many individual wells will have a shorter life than 110 years, but it was assumed that each well will be replaced and that the current distribution will be maintained to the year 2100.) Each of the wells costs approximately

$10 million to drill and establish as producing facilities. The total combined cost of establishing these wells is, therefore, approximately $13 billion. It was assumed that each well requires approximately 10,000 m^2 (as a square, 100 meters on each side) for operation. For the 2-meter scenario, this translates into an additional 520 linear km of required coastal protection, with each of the wells standing on what is in effect its own island. It is also assumed that the enclosed area is raised to maintain a dry work area.

FIGURE 5. TANK FARM FOR OIL STORAGE IN THE NIGER DELTA



Because of the wide, and poorly defined, distribution of the wells throughout the delta, it was not possible to determine precisely how many wells would be threatened by a given scenario of sea level rise. Therefore, it was assumed that the wells were uniformly distributed throughout the delta, and the number of wells threatened by each scenario was estimated using land loss for that scenario. The threatened well count is cumulative with each increase in sea level rise, although newly included wells would not be subject to the full impact of the rise because of their inland location. In other words, a given well that was above the 1-meter contour but still below the 2-meter contour would not threatened by a 1-meter rise. However, that same well would be affected by an additional 1 meter of sea level rise. Such a well would, on average, be inundated by 0.5 meters of water with a full 2 meters of sea level rise.

HARBORS

There are seven major seaports in Nigeria: Apapa (Lagos), Tin Can (Lagos), Port Harcort, Calabar, Warri, Onne, Sapele, and Koko. Of these, the two Lagos ports and Port Harcort handle the majority of the country's shipping transactions. Sea wall estimates were not made for these limited areas because ordinary sea walls are not appropriate protection, and the cost of protecting these segments of shoreline is disproportionate with their length. IPCC (1990) estimated the cost of protecting these harbors at $247 million for a 1-meter rise in sea level. That estimate was used for this study, since the information necessary to improve upon it was not available. For the 0.2-meter sea level rise scenario, a cost of $49.4 million was used; for the 0.5-meter scenario, $123.5 million; and for the 2-meter scenario, $494 million.

RELOCATION

It appears to be impractical to protect many areas in the Mud and Delta Coasts. Hence, retreat is the appropriate option. In this case, the costs of relocation are a real cost of sea level rise. Counts of the villages within each of the estimated zones of inundation for each sea level rise scenario were taken using both the video record and available maps. An average size for each village was estimated by averaging the structure count and structure type of 100 villages that were clearly visible in the video. That average size was then multiplied by the approximate cost to rebuild each of the structures (approximate costs from the private real estate insurance broker B.A. Oyebola, pers. comm, 1991). Counts of the inland villages were based largely on cartographic data. It is believed that many of the smaller inland villages have never been cartographically recorded. Consequently, these counts are probably low. However, the degree of undercounting that has occurred is impossible to determine. All of the coastlines were measured on the video record and maps.

RESULTS

LAND LOSSES

The land-loss results are given in Table 2. Inundation will be responsible for a much larger area of loss than erosion, corresponding to at least 96 percent of the total land loss. This is primarily due to the loss of low-lying marshes and mangrove swamps, particularly in the Niger Delta. The greatest inundation will occur along the low-lying Mud and Delta Coasts. The Barrier/Lagoon Coast, while vulnerable to direct erosion, is, nevertheless, backed by extensive marsh and swamps that will be also be inundated with even moderate rises in sea level. Protection along this section of coastline is in the form of sea walls, combined with some limited beach nourishment.

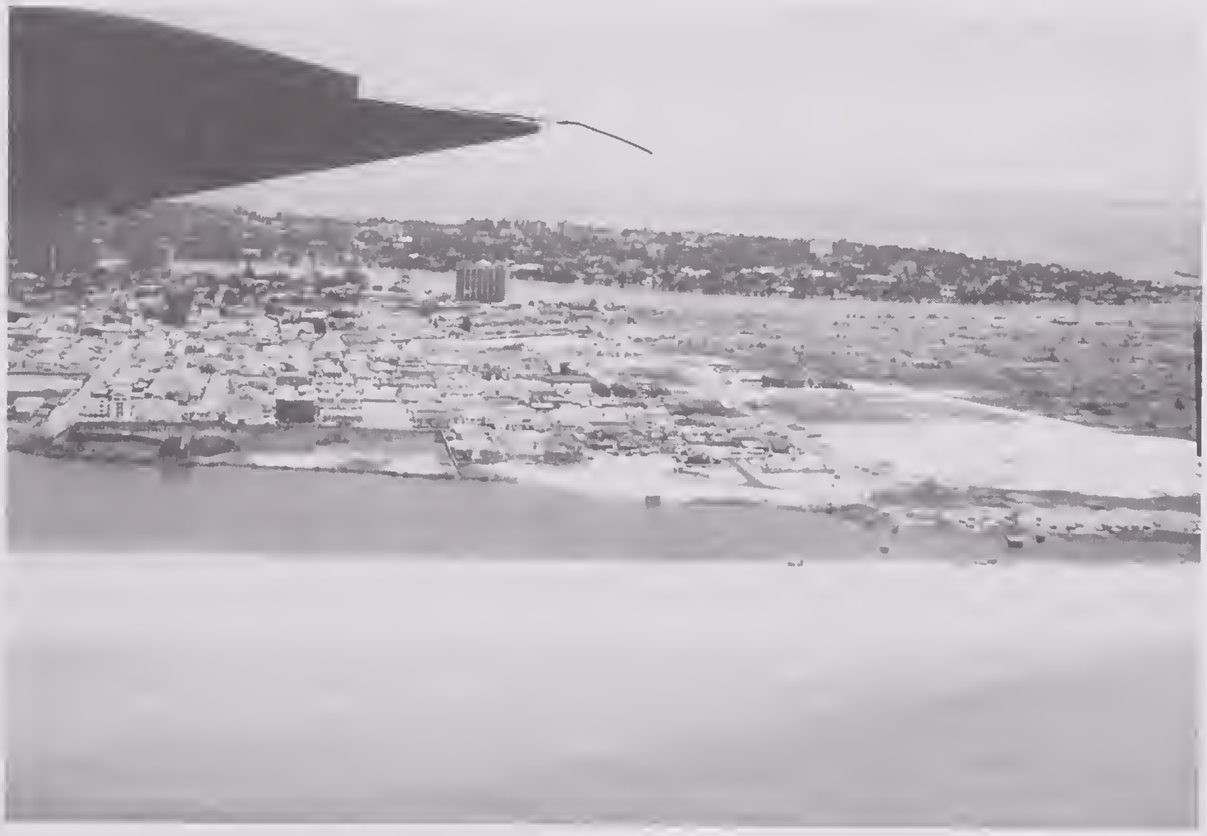
With a 1-meter rise in sea level, the Barrier/Lagoon Coast can be expected to lose as much as 600 km^2 of land. This area of loss includes parts of Lagos and many of the other towns, if no protection measures are initiated. Because of the relative steepness of its beaches, the Barrier/Lagoon Coast is the least subject to erosion losses of the four coastal types. However, existing erosion on the Bar Beach on Victoria Island should be noted (Figure 6). This 6-km section of the coast has among the highest erosion rates in Nigeria, averaging 25 to 30 meters a year. This high erosion is primarily due to the moles (jetties), built to stop the west-east littoral drift from filling in the Commodore Channel, which is the main entrance to Nigeria's largest harbors of Apapa and Tin Can. In addition to beach nourishment, it is believed that, for effective maintenance of the beach, it will be necessary to build offshore breakwaters that will help to dampen the waves before they hit the coastline. The cost of building a stone breakwater, such as the one currently planned for the Bar Beach in Lagos by the Nigerian Federal Ministry of Works, is estimated at roughly U.S. $10 million (Onalaja, 1991).

TABLE 2. LAND LOSS (KM^2) DUE TO EROSION AND INUNDATION BY SHORELINE TYPE

Shoreline Type	**Sea Level Rise Scenarios**			
	0.2 m	**0.5 m**	**1.0 m**	**2.0 m**
Barrier Island				
Erosion	1-4	4-9	8-26	15-52
Inundation	115	280	576	1152
Subtotal	*116-119*	*284-289*	*583-602*	*1,167-1,204*
Mud				
Erosion	NA	NA	NA	NA
Inundation	503	1,008	2,016	3,456
Subtotal	*503*	*1,008*	*2,016*	*3,456*
Delta				
Erosion	26-45	65-112	129-332	258-663
Inundation	2,020	7,388	15,000	18,140
Subtotal	*2,046-2,065*	*7,453-7,500*	*15,125-15,332*	*18,398-18,803*
Strand				
Erosion	4-10	9-24	19-70	38-140
Inundation	75	188	376	537
Subtotal	*79-85*	*197-212*	*396-446*	*585-667*
Total	**2,744-2,772**	**8,942-9,009**	**18,120-18,396**	**23,606-24,130**

NA= Not applicable.

FIGURE 6. VICTORIA ISLAND, SHOWING BAR BEACH AND NEW DEVELOPMENT NEAR SEA LEVEL



Note the new development is protected by only a very narrow sandy barrier strip.

The Transgressive Mud Coast is virtually without sediment supply or barrier beach protection (Figure 4). A 1-meter rise in the level of the sea will result in as much as 2,016 km^2 of land being lost to inundation. For this study, land loss along the Transgressive Mud Coast was estimated solely from inundation, since the Bruun Rule cannot be applied to a silt/mud coast. However, the coast is clearly eroding, contributing to additional land loss. Even with no acceleration in sea level rise, current high rates of land loss through edge erosion alone could be as high as 250 km^2 in the next 110 years along a section of shoreline that is only 83 km long.

The highly complex Niger delta stands to suffer the most in terms of land lost. With a 1-meter rise in sea level, over 15,000 km^2 could be lost to inundation. While the many rivers that traverse the delta once supplied large quantities of sediment to the coast from the hinterland, the construction of as many as 132 dams up the various rivers and tributaries that supply the Nigerian coast with sediments have robbed much of that supply (although most are small earthen dams used primarily for irrigation and water supply) (Ibe, 1988).

The problem of land loss in the delta may be further compounded by the fact that the rates of relative sea level may be higher than the scenarios used in this study due to local subsidence within the delta. The area is known to be part of an actively subsiding geosyncline (Awosika et al., 1989). On top of this are the continued and expanding operations of the oil industry (Figure 5). The effects of fluid extraction, known to potentially cause localized subsidence in other parts of the world, have not been adequately addressed in the Niger delta. Local subsidence rates are presently being studied (mostly along the Barrier/Lagoon Coast), but the only reliable figures available to date show subsidence rates of more than 2.5 cm/yr at the site of a tank farm (after correcting for loading effects of the oil tanks) (Awosika et al., 1989). Therefore, it is highly probable that relative sea level rise in the delta will exceed the eustatic trend (Milliman et al., 1989).

The Bruun Rule estimates show that as much as 663 km^2, or nearly all, of the estimated 700 km^2 of the 20 sandy barriers along the Delta Coast could be lost to erosion with a 2-meter rise in sea level (Table 2). Even though there are small areas above 2 meters in elevation, and/or wider than certain Bruun Rule retreat estimates, those areas were considered to be lost, since as inundation proceeds in the delta behind, the small islands would begin eroding on all sides. However, erosion represents only a small percentage of the total potential land loss along the Delta Coast (0.8 to 3.5 percent). Inundation is much more important than erosion because of the vast expanses of low-lying mangrove swamps behind the barriers.

The Strand Coast to the east shares many of the characteristics of the delta but has only a relatively narrow strip of mangrove swamps backing a system of narrow barrier islands. Because the back-barrier mangrove swamps only reach inland up to 5 to 7 km, erosion constitutes a higher percentage of the total Strand land loss than along the Delta Coast (4.6 to 20.7 percent for the Strand Coast versus 0.8 to 3.5 percent for the delta). Nevertheless, like the other coastal types, this coastline exhibits an overall pattern of substantially higher land loss from inundation than from erosion. The main problem here currently is flooding due to seasonal rains and low topography. An increase in sea level of only a small amount will only exacerbate the problem of flooding and inundation in a region that is already prone to these problems.

ECONOMIC LOSS

Like land loss, inundation can be expected to inflict the greatest economic loss on the country. The expected inundation could stretch along over 70 percent of the Nigerian coastline and many square kilometers inland. As the Nigerian economy depends heavily on the fisheries and oil production in these low-lying areas, such losses would have a significant, adverse effect on the national economy.

Because of the impracticality of protecting the many hundreds of small villages, principally throughout the delta, they will be lost and need to be relocated inland with increasing sea level rise, further adding costs. The number of villages estimated to be lost with the various sea level rise scenarios, along with their estimated values, are presented in Table 3. Each of the villages is estimated to have an average of 86 structures.

TABLE 3. ESTIMATED VILLAGE COUNTS AND VALUES AFFECTED BY SEA LEVEL RISE (MILLIONS OF U.S. DOLLARS)

Location of Village	**Sea Level Rise Scenarios**							
	0.2 m		***0.5 m***		***1.0 m***		***2.0 m***	
	Count	*Value*	*Count*	*Value*	*Count*	*Value*	*Count*	*Value*
Villages Along Barrier	7	$2.2	16	$5.1	32	$10.2	58	$18.5
Villages Along Mud	30	$9.5	75	$23.9	150	$47.7	200	$63.6
Villages Along Delta	110	$35.0	275	$87.5	550	$175.0	800	$254.5
Villages Along Strand	16	$5.1	40	$12.7	80	$25.5	125	$39.8
Total	**163**	**$51.8**	**406**	**$129.2**	**812**	**$258.4**	**1,183**	**$376.4**

Table 4 lists the total economic value of the loss of property for each of the four coastal types based on each of the four different sea level rise scenarios, including village values. Table 5 illustrates the structure type and value in U.S. dollars based on the 1991 exchange rate of 10 Nigerian naira to 1 U.S. dollar.

TABLE 4. RANGE OF VALUE LOST BY COASTAL TYPE AND SEA LEVEL RISE SCENARIO* (MILLIONS OF 1990 U.S. DOLLARS)

Coastal Type	**Sea Level Rise Scenarios**			
	0.2 m	*0.5 m*	*1.0 m*	*2.0 m*
Barrier Island	$1,764	$4,411	$8,821	$11,762
Mud	12	26	50	66
Delta	54	160	407	5,004
Strand	6	13	26	2,980
Total	**$1,836**	**$4,610**	**$9,254**	**$19,812**

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* Excludes harbors and oil wells.

Clearly, the greatest overall value lost will be along the Barrier Island Coast, ranging from just under $1 billion U.S. with a 0.2 meter sea level rise, to almost $10 billion with 2.0 meters of rise. This is principally due to the loss of the greater Lagos urban area. This is followed by the Delta Coast. However, there is a significant increase in the loss-value of the delta with an increase from 1.0 to 2.0 meters of sea level rise. This is because of two large cities that lie between the 1.0- and 2.0-meter contours and would remain relatively unaffected by 1.0 meter of sea level rise, but would be lost with 2.0 meters of rise.

TABLE 5. ESTIMATED VALUE OF VARIOUS STRUCTURE TYPES

Type of Structure	Estimated Value
10-Story High-Rise	$9,500,000
Low-Rise Commercial (less than 5 stories)	4,000,000
Factories, Large	1,000,000
Factories, Small	500,000
Urban Single-Family (avg. 10 pers)	500,000
Urban Four-Family Flat (avg. 7 pers./family)	50,000
Suburban Bungalow (avg. 20 pers.)	7,500
Rural, Block House (avg. 10 pers.)	5,000
Rural/Suburban Wood/Mud w/ Metal Roof (avg. 10 pers.)	1,000
Rural Wood/Mud w/ Thatched Roof	500

PEOPLE DISPLACED

Another significant, though unquantifiable, cost will be a probable massive "environmental refugee" migration. For this study, village relocation was assumed to mean the rebuilding of the lost structures and reoccupation of them by the same people. It is not likely that this will be the case. It is probable that many of the relocated villagers will migrate to the urban centers instead of relocating to a traditional village lifestyle. At the same time, the population of the cities will also be in flux as the encroaching sea invades the urban and suburban areas. No assumptions were made as to where these people will go and how they will live. Therefore, it was not possible to estimate what the costs might be for such a potentially massive urban relocation. Table 6 lists the estimated total number of people who will be displaced by the four sea level rise scenarios and the percentage of the total Nigerian population (est. 115 million, P.C. Globe, 1989). The table represents the number of people who will be displaced based on a no-protection scenario of land area lost.

TABLE 6. ESTIMATED NUMBER OF PEOPLE DISPLACED BY SEA LEVEL RISE

Coastal Type	Sea Level Rise Scenarios			
	0.2 m	*0.5 m*	*1.0 m*	*2.0 m*
Barrier	0.60	1.50	3.00	6.00
Mud	0.03	0.07	0.14	0.18
Delta	0.10	0.25	0.47	3.21
Strand	0.01	0.034	0.069	0.61
Total	**0.74**	**1.854**	**3.679**	**10.00**
% Population	0.65	1.61	3.20	8.70

OTHER POSSIBLE IMPACTS

Increased flooding during the rainy season can be expected. Many areas that are currently subject to extensive rainy-season flooding will experience more frequent and severe flooding. Some areas will be lost altogether to inundation, and large areas of periodic flooding will extend progressively farther inland. Where many of the villages that are presently subject to recurrent flooding are somewhat equipped to withstand the intermittent high waters (e.g., build on stilts), villages farther inland are not so equipped. This new intrusion of flood waters will require physical restructuring of existing buildings and structure loss among the newly affected villages.

Increased saltwater intrusion, not addressed in this study, is feared to contaminate aquifers throughout all of the coastal regions of Nigeria with rising sea levels. The population in Nigeria's coastal zone depends heavily on ground water for its freshwater needs. In Lagos, for example, some 60 percent of the estimated 400,000 cubic meters per day of water required is taken from the shallow, unconfined aquifer that extends from ground level to 12 meters below (Ibe and Awosika, 1989). Port Harcort, some 40 km inland in the delta, is relatively safe from inundation (with the exception of the port), since most of the city is on slightly higher ground. However, some municipal wells in the city extract as much as 90,000 gallons per hour, and increased sea level rise is expected to result in increased salinity of that essential ground water (Awosika et al., 1989).

Even when all areas considered to be of value are protected (or relocated) in the Important Areas and Total Protection scenarios, extensive marsh areas and mangrove swamps will still be lost along both the Delta and Strand Coasts, since there is no practical way to protect them from the encroaching sea. It was not possible to predict the economic impacts of the loss of these largely undeveloped areas. However, this is an important consideration in that these areas support much of the large fishing industry of Nigeria, and their loss will probably contribute significantly to the economic stress on the country.

TABLE 7. PROTECTION OPTIONS BY SHORELINE TYPE (EXCLUDING OIL WELLS) FOR IMPORTANT AREAS PROTECTION

Coastal Type	Protection Option	Protection Length (km)
Barrier/Lagoon	Open Coast Sea Wall	25*
	Sheltered Coast Sea Wall	50*
	Nourishment	6
Mud	Open Coast Sea Wall	1
	Sheltered Coast Sea Wall	3
Niger Delta	Open Coast Sea Wall	22**
	Sheltered Coast Sea Wall	44**
Strand	Open Coast Sea Wall	3
	Sheltered Coast Sea Wall	6

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*These lengths increase to 205 km and 524 km, respectively, when full protection is implemented because of the added back-barrier and lagoon protection.

**These lengths increase to 44 km and 66 km, respectively, with the 2.0-meter scenario, from the 1.0 meter and lower scenarios because three additional major cities are affected only with 2.0 meters of sea level rise.

PROTECTION COSTS

Protection costs were based on the length and type of protection required (Table 7). The cost of protecting the coastlines of the country against a 1-meter rise in sea level potentially ranges from $557 million to nearly $1.5 billion, depending upon whether only important areas are protected, or if total protection is implemented (Table 8). With a 1-meter rise in sea level, perhaps as much as $9 billion in economic value could be lost without considering the value of the oil wells (Table 4). When the cost of the loss of affected oil fields is included, that figure increases to as much as $19 billion. Along with this economic cost, as many as 3.7 million people could be displaced (3.2 percent of the total Nigerian population) (Table 6). These figures only represent the situation that would occur if sea level were to rise with current patterns and levels of human development.

TABLE 8. PROTECTION COSTS

	Sea Level Rise Scenarios							
	0.2 m		*0.5 m*		*1.0 m*		*2.0 m*	
Protection	*Impt*	*Total*	*Impt*	*Total*	*Impt*	*Total*	*Impt*	*Total*
Nourishment	$7-34	$7-34	$15-58	$15-58	$27-98	$27-98	$51-179	$51-179
Sea Walls	9-55	51-243	32-85	168-384	88-148	445-674	283-472	1408-1686
Relocation	–	49	–	124	–	248	–	358
Oil Wells	12	12	52	52	195	195	801 801	
Harbors	50	50	124	124	247	247	494	494
Total	**$78-151**	**$169-388**	**$223-319**	**$484-742**	**$557-689**	**$1,163-1,463**	**$1,629-1,946**	**$3,112-3,697**
% GNP	0.2-0.3	0.5-1.1	0.6-0.8	1.3-2.0	1.5-1.8	3.2-4.0	4.4-5.3	8.5-10.1

NO PROTECTION

In the No Protection scenario, the cost of protecting the coastline would be zero, but the maximum amount of land would be lost. The amount of land lost would be the totals shown in the land-loss section (Table 2), which does not take shore protection into account, and the total economic value of structures, not including oil wells, reflected in Table 4.

PRESENT PROTECTION

While other studies have considered existing protection (Niang et al., these proceedings), in the case of Nigeria, it proved impossible to acquire a comprehensive accounting of all present protection projects. Therefore, no attempt was made to estimate costs of maintaining protection of shorelines currently protected.

IMPORTANT AREAS PROTECTION

For the case of protecting important areas, all areas with medium to high development, defined as having a structure concentration of 15 percent or greater over an area of 1 square kilometer, are protected. This includes most of the settled areas, since much of the Nigerian population is concentrated in urban areas. Estimates of the total length of important coastlines requiring protection, based on medium to high development, were made from the video record and the cartographic and demographic data that were available. In practice, this corresponded to the towns depicted on available maps. The protection requirements for this scenario are listed in Table 7, together with suggested protection methods. The total costs for the Important Areas Protection case are listed in Table 8.

In addition, oil wells will require significant and costly protection. The 1-meter sea level rise scenario would require a total of 430 km of sea wall and fill, totalling nearly $200 million. These figures represent a best estimate based on the available information at the time of this study.

TOTAL PROTECTION

The final scenario for protection from sea level rise is to protect all coastal areas along the Barrier Island Coast, including the beach nourishment at Victoria Island, harbors as estimated by the IPCC, and all important areas in the other three coastal sections. The largest difference between this scenario and the Important Areas case is the inclusion of protection, in the form of sea walls, for the entire Barrier Island Atlantic Coast, including the shores of the Badagry Creek and the Lagos and Lekki Lagoons backing the Barrier Islands, and the relocation of the numerous villages that will be threatened. This maximum protection scheme added some 474 km of sheltered sea wall and 180 km of open-coast sea wall to the total of sea wall required. Table 8 reflects both the costs of the increased sea wall and the relocation of villages. To assess the costs of protecting the coast of Nigeria from sea level rise versus the economic value of the properties lost, the cost of Total Protection was compared with the value of the structures lost. It can be seen in Table 9 that the cost of protection is much less than the property value at risk. However, this should not be treated as a cost-benefit analysis.

TABLE 9. PROTECTION COST VERSUS PROPERTY VALUE (MILLIONS OF 1990 U.S. DOLLARS)

	Sea Level Rise Scenarios			
	0.2 m	*0.5 m*	*1.0 m*	*2.0 m*
Protection Cost	$170 - 388	$484 - 742	$1,163 - 1,463	$3,112 - 3,518
Property Value	$1,837	$4,615	$9,314	$19,831

COMPARISON WITH IPCC (1990)

The Intergovernmental Panel on Climate Change produced a worldwide estimate of the cost of a 1-meter rise in sea level using desktop methods (IPCC, 1990). For each country, the IPCC estimated the cost of protecting all the low-lying coastline with a population of $\geq$ 10 people/km^2. This includes all the estuaries and lower reaches of rivers that would be affected by sea level rise. The IPCC (1990) estimated the cost of protecting Nigeria at U.S. $3,162 million for a 1-meter rise in sea level, including $247 million in harbor upgrades. This did not include protection of the Niger delta, which was estimated to have a population of < 10 people/km^2.

For the same scenario, this study suggests a Total Protection cost of approximately $1.4 –1.8 billion, or roughly 50 percent of the IPCC cost. While the assumptions of the two studies are not exactly comparable, several interesting points can be raised.

1. *Length of sea walls.* The IPCC estimated 1,955 km of required protection, even though there was no protection within the Niger delta. This study identified a requirement for 1,288 km of sea wall protection with a 1-meter rise in sea level (rising to 1,372 km of required sea wall with a 2-meter rise).

2. *Cost of sea walls.* The IPCC (1990) used about 38 km of city sea wall at a cost of U.S. $18 million/km with a total cost of U.S. $665 million, whereas our unit costs were just under $2 million/km. For the rural areas, the unit cost of our sea walls was also generally lower than that used by the IPCC.

3. *Beach nourishment.* This study proposed nourishment for only 6 km of beach, as opposed to 25 km in IPCC (1990). However, if current plans for development east of the Bar Beach on Victoria Island (Lekki) proceed, requirements for beach nourishment will be increased by 15 km, adding up to $195 million for a 1-meter sea level rise scenario.

It is believed that the figures in this paper, based on the in-country data collection, reflect more accurately the actual costs of possible sea level rise based on current conditions.

APPROPRIATE RESPONSES

Nigeria derives as much 90 percent of its GNP from its oil reserves. Unfortunately, this income is highly unstable with fluctuating world oil prices and is currently on a decline with the present world oil glut. Although the Nigerian GNP was reported to be approximately $36.8 billion in 1989 (P.C. Globe, 1989), most of it is spent on simply trying to feed its people. The cost of protecting the coastlines of the country against a 1-meter rise in sea level range from $1.2 billion to $1.5 billion, or a range of approximately 3.3 to 4.1 percent of one year's 1989 GNP. However, with a 1-meter rise in sea level, perhaps as much as $9 billion in economic value could be lost, and as many as 3.7 million people displaced (3.2 percent of the total Nigerian population). If the cost of drilling oil wells is considered, the value at risk is $19 billion.

These figures only represent the situation that would occur if sea level were to rise with current patterns and levels of human development. Yet, the following trends point to rapid development of the coastal zone in the coming century: (1) high birth rates, (2) greater affluence from oil revenues, (3) immigration from neighboring countries, and (4) increased rural development programs and the need to feed the fast-growing population.

PROTECTION

The major cost of protecting against sea level rise in Nigeria will be sea wall construction along the Barrier Island Coast, along both the Atlantic Coast and the vulnerable inland shores of Badagry Creek and the Lekki and Lagos Lagoons. The protection of the approximate 1,300 oil wells located throughout the delta will add significant cost. However, these wells constitute an investment of some $13 billion. Therefore, such protection is most warranted.

Since the vast majority of the population and industry within the coastal zone in Nigeria is located on very low-lying land, protection of these areas will be essential. Fortunately, most of the population and economic resources at risk are in towns. Therefore, the cost of protection, compared to the cost of retreat, is relatively modest. In this regard, it would seem that the problems facing Nigeria are somewhat different compared to other low-lying countries, such as Egypt and Bangladesh, where large agricultural populations are at risk from sea level rise (Milliman et al., 1989).

The major harbors must also be protected, as they are crucial to the economic health of the country. Soft protection in the form of beach nourishment is a fairly minor concern, relative to the country as a whole. Coastal tourism is relatively young in Nigeria. While beaches west and east of Lagos are used for informal, low-intensity tourism, there is negligible tourist infrastructure in the form of hotels and associated facilities in place there. So sea walls are recommended for these areas, only in the case of total protection. However, the 6-km Bar Beach at the west end of Victoria Island (Lagos), often referred to locally as the "Hollywood of Nigeria," is a significant exception (Figure 6). This area is highly developed with numerous hotels, parking, and other tourist facilities. Beach nourishment is suggested as the best response here, both for the Important Areas and Total Protection scenarios, because the sandy beach is the area's major tourist attraction.

Recently there has been sporadic resurgence of growth in the construction of hotels, recreation, and roads for coastal-based tourism along the Bar Beach, with plans for further development in the near future (Lekki Beach) (Awosika et al., 1991). If such development occurs, more extensive beach nourishment will be required at much greater costs than presented here.

RELOCATION

Relocation of villages will be required regardless, of sea level rise scenario or protection scheme. Because of the great number of channels within the delta, it is simply not practical to attempt to armor the shorelines to protect the hundreds of villages located throughout the delta. The total length of sea wall required would be extremely difficult to calculate, but it is clear that the figure would be uneconomic from a protection perspective. It would also destroy the wetlands that comprise the delta as surely as sea level rise. Therefore, the only practical solution is to relocate the villages on an as-needed basis as the sea encroaches on the delta.

Although there are no rivers within the Mud Coast region, there are many small villages and towns (see Figures 3 and 4). Like the villages in the delta, it would not be practical to attempt to armor each of them. In addition to the high number of small villages that would require protection, the cost of transporting the required construction materials would add even more cost, since all transport would have to be via shallow draft vessels and on foot or draft animal, the only means of transport to most of the villages. Therefore, relocation was also considered the most practical solution to the problem of inundation for the villages within the Mud Coast region.

The many hundreds of villages that will inevitably be lost with sea level rise must be considered. Perhaps a million villagers will be displaced with a 2-meter rise in sea level. This is an environmental refugee problem on a large scale involving the displacement of large numbers of people from their ancestral homes to a new environment and way of life. The social costs of this human displacement, in terms of disruption, could be severe and should not be overlooked (UNFPA, 1991). The cost of the necessary relocation can be distributed over time if a program of anticipatory relocation is undertaken before the need becomes imperative.

MITIGATIVE MEASURES

Several steps can be taken to mitigate the impacts of any future sea level rise on the coast of Nigeria (Awosika et al., 1989). Based on this study, the following measures seem most useful.

SETBACK LINES

In the U.S., setbacks based on up to 60 times the annual erosion rate have been recommended (National Research Council, 1990). Setbacks in Nigeria should be similarly derived.

CONTROLLED URBANIZATION

Continued urban expansion in the coastal zone should be controlled. Construction plans for capital facilities, such as roads, buildings, and sewers, should consider projected sea level rise.

PUBLIC AWARENESS PROGRAMS

It is critical that private developers and the general population be informed of the potential dangers of living and building in the near coastal zone.

EVALUATION OF LOW-COST RESPONSES

Low-cost, low-technology erosion control techniques, such as sand-bagging, should be evaluated.

SUGGESTED FOLLOW-UP ACTIVITIES

This preliminary study has shown that the entire coastal zone of Nigeria is physically vulnerable to sea level rise and thus could have very serious socioeconomic consequences. However, this study is based on relatively limited data. As a follow-up to this study, a number of projects are suggested.

DRAINAGE

This study did not consider the problems of drainage associated with sea level rise. These could be very costly, given the low elevation of the Nigerian coast, and should be fully investigated.

HISTORICAL ANALYSES OF SHORELINE EVOLUTION

While some data already exist on shoreline evolution (Ibe, 1988), the information should be expanded to provide data to calibrate future shoreline behavior and, hence, provide better estimates of physical impacts.

ACCURATE TOPOGRAPHIC ANALYSES

These analyses of the entire Nigerian coastal zone are critical for accurate assessment of the consequences of sea level rise. A widely based program of topographic surveys throughout the coastal zone should be immediately undertaken. This would also help to control serious flooding that already exists.

ACCURATE DEMOGRAPHIC ANALYSES

Such analyses, particularly of the delta region, are necessary to assess the size of the population that will be at risk and, consequently, to assess the costs of required remedial activity.

ASSESSMENTS OF FUTURE DAM CONSTRUCTION

The impacts of dam construction on the Niger and its tributaries should be considered. Also, the technical feasibility of sediment bypassing at existing dams should be investigated.

ENVIRONMENTAL REFUGEES

Responses to sea level rise should consider social as well as economic factors, such as the displacement of people within each of the four geomorphic coastal units.

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CASE STUDIES OF CONTINENTS AND LARGE ISLANDS

THE IMPACTS OF SEA LEVEL RISE ON ARGENTINA'S COASTLINE

Gerardo M.E. Perillo and Maria Cintia Piccolo
Instituto Argentino de Oceanografía
Bahía Blanca, Argentina

INTRODUCTION

In recent years, a growing concern has developed among scientists about global sea level rise as a consequence of the "greenhouse effect." Hoffman (1984) predicts an increase in mean sea level on the order of 1 meter within the next 60 to 150 years. Present-day tendencies, based on historical tidal records on stable coastal locations, indicate that sea level will rise at a rate of 1 to 2 mm/year, although an NRC (1987) report suggests that these rates may increase parabolically with time.

Low-lying coasts will suffer the major impacts of sea level rise, even if the collateral effects associated with storm surges, variations in river discharge, and other oceanographic and meteorological factors are not taken into consideration. The economic, social, political, environmental, and cultural damages may be extremely large. Government and private organizations should be aware of these dangers and should initiate the adequate strategic management of the coastal zone as soon as possible.

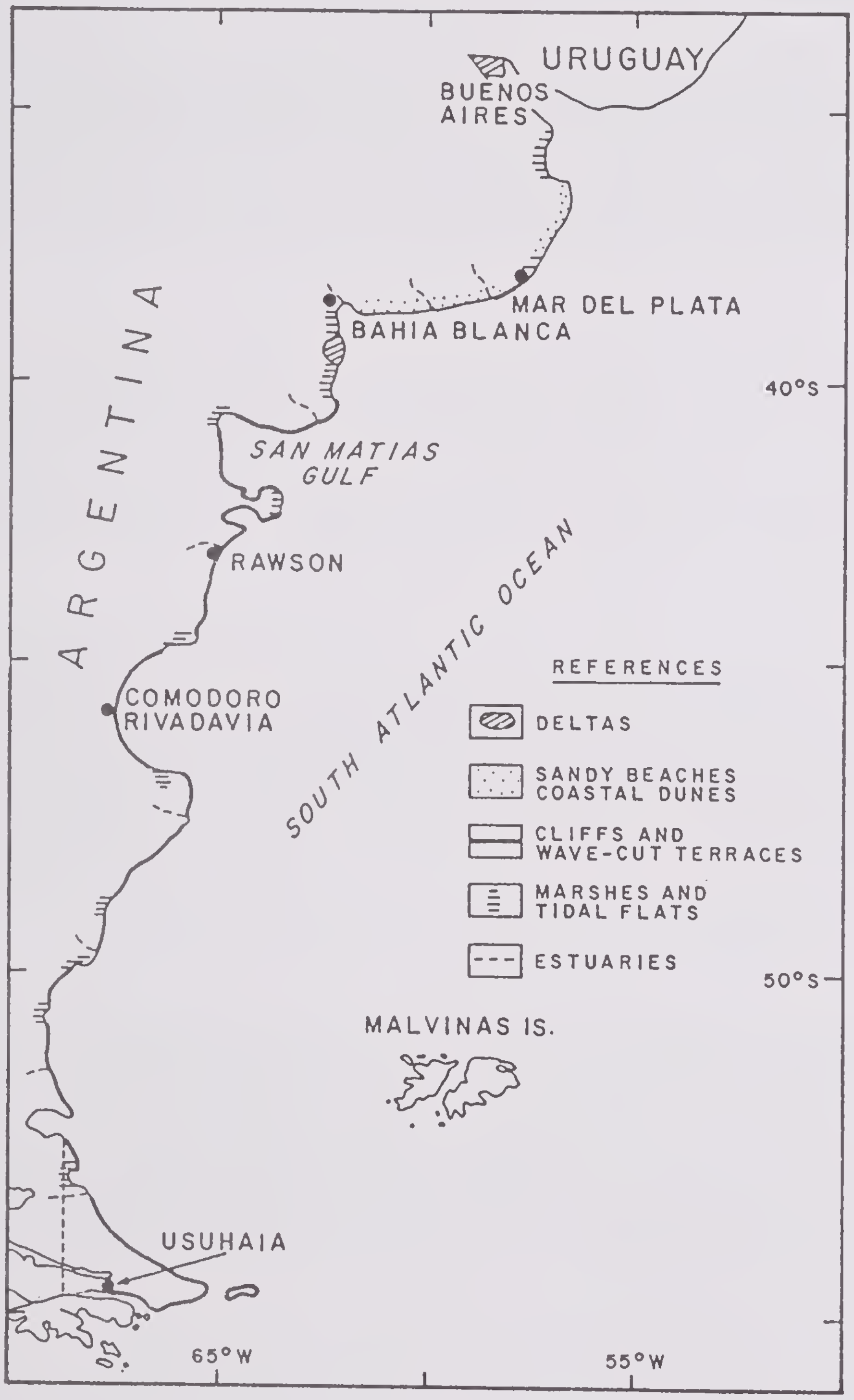
The worst effects of sea level rise are expected in coastal developing countries. Therefore, the Argentine government, through the Ministerio de Relaciones Exteriores, has recently appointed the Comité Nacional para el Programa Hidrológico Internacional and the Comité Nacional para la International Association for the Physical Sciences of the Ocean (CNIAPSO) to establish a working group to assess the impact of sea level rise on the Argentine coast. The working group has been initially formed by researchers and university professors from a large number of organizations covering a wide range of disciplines ranging from oceanography, geology, geography, and hydrology to economics, law, and urban studies.

This paper briefly describes the Argentine coast and the initial estimate and reasons for the selection of the case study region. Because the working group has only been in existence for 6 months, and because of a lack of any financial support, a full report on the case study was not possible at this time. The working group has now on hand videotapes of over 1,600 km of the Argentine coast made by the University of Maryland in collaboration with Argentine scientists, and the tapes are being analyzed following the criteria developed by Dennis et al. (1991).

PHYSICAL CHARACTERISTICS OF THE ARGENTINE COAST

Argentina is located on the southern tip of the South American continent, with over 5,700 km of coastline facing the south Atlantic Ocean (Figure 1). Bordering the coastline is a large continental shelf varying from 150 km to over 800 km wide, as it is limited by the 200-meter isobath. The outer and middle shelves are practically devoid of major relief. However, the inner shelf between 36°S and 44°S has a large number of shoreface-connected sand ridges that may be associated with the net coastal retreat affecting the Argentine coast (Parker and Perillo, 1976; Swift et al., 1978; Gómez and Perillo, 1992a).

FIGURE 1. CHARACTERISTICS OF THE ARGENTINE COASTLINE



From north to south, the shoreline starts with the Río de la Plata estuary. The river, formed by the confluence of the Parana and Uruguay Rivers, is one of the widest in the world, although very shallow, especially in its inner and middle reaches. The head of the estuary is the Parana River delta, a low-lying area with a large advance rate of over 10 meters/year into the Río de la Plata, due to the high sediment load provided by the Parana River.

The Argentine coast of the Río de la Plata is low and subject to inundation due to major storms locally called "southeasters." The surges from these storms produce elevations in the river level of up to 4.5 meters. However, defenses have been constructed to protect the most densely populated area of the country. Samborombon Bay is a marshy, tidal flat area connected with the Salado River basin. The basin that extends inland with very low relief is subject to periodic inundation due to heavy precipitation. The impacts of sea level on this area are at least twofold: (1) the direct effect of sea level rise advancing over the flat area, and (2) the increase of the base level for the discharge of the Salado and other minor rivers and artificial channels. As a result, eliminating the excess water will become more difficult, causing tremendous economic damage to one of the richest agricultural zones of the country.

The rest of the Buenos Aires province shoreline down to Bahía Blanca estuary is formed by sandy beaches backed by coastal dunes of varying widths. Laguna Mar Chiquita is the only typical microtidal coastal lagoon in Argentina. The coast between Mar Chiquita and Miramar (30 km south of Mar del Plata) is composed of cliffs formed by Plio-Pleistocene semiconsolidated sediments, with heights ranging from a few meters to 25 meters. However, the cliffs border to the north and south lower Paleozoic quartzites that are the seaward limit of the Sierras de Tandil hill system, outcropping just in the downtown coast of Mar del Plata city.

The remnants of a late Pleistocene–early Holocene delta complex form the coast from the Bahía Blanca estuary to San Blas. The present-day delta of the Colorado River has now a 60-km N-S linear stretch of the coast between Bahía Blanca estuary and Bahía Anegada, showing a clear example of coastal retreat. Bahía Blanca estuary and Bahía Anegada show extensive tidal flats, with sparse Spartina and Zoostera patches that cannot be considered as low marsh areas. Perillo (1989) indicates that the area is in an accelerated erosional stage due to the lack of sediment input from the rivers and the inner shelf.

The Patagonian coast, from the Negro River to the Maguellan strait, is bordered by cliffs composed mainly of marine and continental Tertiary semiconsolidated sediments and wave-cut terraces. The cliffs vary in height from 10–15 meters to 150 meters in parts of Santa Cruz province and south of San Sebastián Bay in Tierra del Fuego. The bay consists of late Pleistocene glacial sediment derived from the basement till of a large glacial tongue that crossed the island from San Sebastián Bay to Inutil Bay (Chile). The Beagle Channel coast is formed by Cretaceous rocks of marine origin.

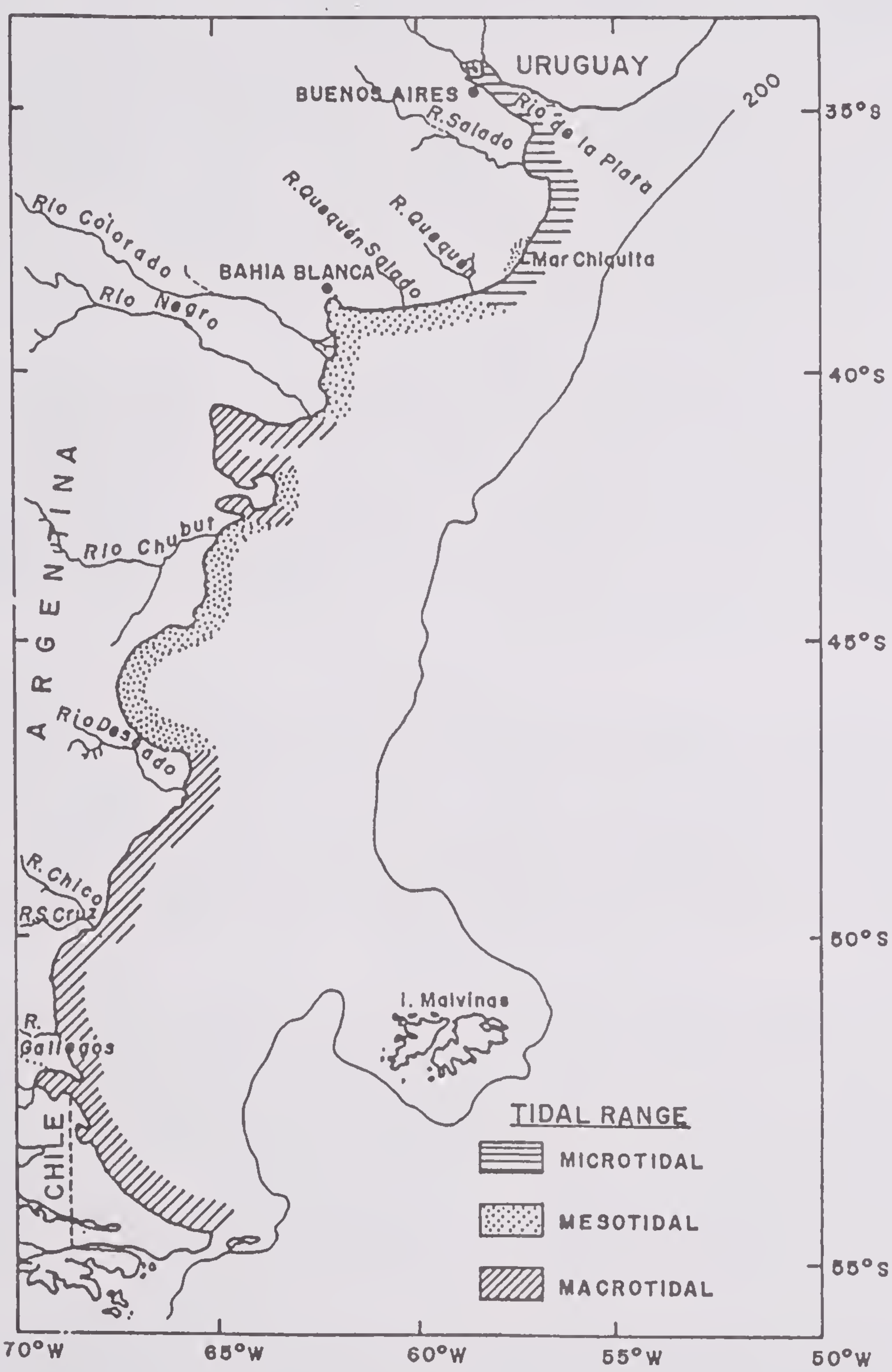
Although many beaches associated with the Patagonian coast are formed by medium to coarse sands, the characteristic sediments of these beaches are pebbles locally known as *rodados patagónicos*. The pebbles are the lag deposit formed by reworking and winnowing of Quaternary sediments of continental origin. Due to the large tidal variation on the southern coast of Argentina, the pebbles concentrate near the mean high and low tide levels, where wave energy can act for a relatively longer time, whereas in between, the extended beaches are normally composed of fine sand and sometimes mud (Perillo and Codignotto, 1989).

The general outline of the Patagonian coast presents a series of embayments and gulfs, a couple of which are semienclosed. Some of the gulfs (i.e., San Matias, San José, and Nuevo) may have been formed by the inundation of large semienclosed depressions commonly found on the Patagonian coast and locally known as *bajos*. The gulfs may be as deep as 120–150 meters at their center; the sills at their mouths are only 30–40 meters deep.

ESTUARIES

The Argentine coast has 10 large estuaries (Figure 2) and another 20 of lesser importance. Within the most developed estuaries are the Río de la Plata and Bahía Blanca estuary, along with the Quequén, Colorado, Negro, Chubut, Deseado, Santa Cruz, and Gallego River estuaries. Each of these estuaries has quite different characteristics. Most of them may be classified as typical coastal plain estuaries. Others, especially those of the Santa Cruz province, may be classified as *rías*, since they have been formed by the flooding of river valleys on high-cliff coasts (Perillo, in preparation).

FIGURE 2. CLASSIFICATION OF THE ARGENTINE COAST BASED ON TIDAL RANGE



Relatively little work on the geomorphology and dynamics of Argentine estuaries has been done. The most studied estuaries are those more important from an economic viewpoint, such as the Río de la Plata, the Bahía Blanca estuary, Quequén, and Chubut.

Mar Chiquita has all the characteristics of a coastal lagoon developed in a microtidal environment. Nevertheless, there are at least two other bays that may be related with coastal lagoons, such as Caleta Valdés (on Valdés peninsula) and San Sebastián Bay. Both are closed by very long, pebbly spits formed by southward littoral drift. However, only Mar Chiquita and Caleta Valdés have a proper inlet, while the mouth of San Sebastián Bay is quite wide. On the other hand, San Antonio Bay and Caleta Los Loros are also coastal lagoons, but were developed in the macrotidal northern coast of the San Matías Gulf.

SEA LEVEL VARIATIONS

The Pleistocene in the Northern Hemisphere is characterized by four glacial periods, although Suguio et al. (1985) have shown that there is no direct temporal correlation with the Southern Hemisphere. According to the literature, the best documented glacial period, Wisconsin, lowered sea level on an order of 130 meters (about the limit of the shelf break) some 18,000 years ago. It was estimated that sea level rose at a rate of about 8 mm/year within the first 15,000 years, but changed to the present rate (1-2 mm/year) in the last 3,000 years.

However, further evidence presented by Fairbridge (1961) suggests that the rising process was also marked by strong oscillations. Some of them occurred within the last 7,000 years and raised the sea above its present level. For example, Aliotta and Perillo (1985, 1990) have described a series of wave-cut terraces at 13 to 16 meters below present sea level at the mouth of the Bahía Blanca estuary. They estimated the age of the terraces to be 7,000 to 8,000 years B.P. Gomez and Perillo (1992b) have correlated these terraces with typical tidal-flat mud layers found by Gomez and Perillo (1992a) underneath shoreface-connected sand ridges at depths of 12 to 15 meters.

On the other hand, González (1989) has observed in the inner Bahía Blanca estuary a series of five sand-shell ridges located between 7 and 12 meters above present sea level and dated from 5,990 to 3,560 years B.P. using C^{14}. These ridges have developed over tidal flat deposits. González (1989) also shows a series of other undated ridges closer to the present main channel of the estuary, which may indicate younger episodes during the regression process. There are no further indications of other possible fluctuations of the sea level as it returned to a position somewhat below the present.

As indicated, sea level variations are nowadays being analyzed using long-term tidal records. However, most tidal gauges in Argentina have records less than 100 years old. Furthermore, those having longer records, for instance in the Río de la Plata and Bahía Blanca estuary, cannot be used with confidence, since they are affected by the local dynamics associated with estuarine circulation and river discharges. Lanfredi et al. (1988) have considered that the most reliable tidal gauge for making such a calculation is Puerto Quequén, with 64 years of information. They obtained a rate of sea level rise of 1.6 mm/year, quite coincident to those found in other parts of the western Atlantic.

Figure 2 shows the distribution of tidal ranges of the Argentine coast, which varies somewhat from that published by Davies (1964) and other authors afterward. The coast is microtidal up to Necochea, becoming mesotidal in the open areas down to the Deseado River estuary. In the northern Patagonian gulfs and southward of Puerto Deseado, tidal ranges are macrotidal, reaching maximum values of 12 meters in San Sebastián Bay and Río Gallegos.

WAVES AND LITTORAL CURRENTS

There are very few observations of wave parameters on the Argentine coast. The best documented areas are associated with harbor entrances (i.e., Mar del Plata, Quequén, Bahía Blanca, Rawson) or areas proposed as ports, like the Punta Medanos sector in Buenos Aires province. Swells are mostly related to the migration of cyclonic centers moving almost parallel to the coast, but beyond the continental shelf. As a result, most of the time the northern coast (Buenos Aires province) receives waves coming from the S and SE quadrants, while the middle and southern portions of the country are affected by progressively larger percentages of waves from the E and NE quadrants.

Swells have periods normally between 6 and 16 seconds and maximum heights of 1 meter. However, locally generated waves have periods below 6 seconds and may be as high as 5.5 to 7 meters.

Littoral currents produced by wave action are strong along the coast, although longshore sediment transport is more evident on the sandy shores. For instance, Buenos Aires province has a dominant northward transport from Necochea to Sanborombon Bay. Other areas, like the spits that close Caleta Valdés, have encountered transport directions since the longer spit indicates a southward transport, opposite to the shorter spit located on the other side of the inlet. Nevertheless, estimated alongshore sediment transport ranges from 300,000 to 1,000,000 m^3/year (Schnack et al., 1990).

The Mar del Plata area is practically the only coastal region where significant shore protection was constructed. The shape of the Mar del Plata harbor modified the net northward longshore transport of sediment, resulting in heavy erosion and the disappearance of beaches. To protect the coast, a "program" indiscriminately constructed groins along over 60 km of the coast. This resulted in still greater damage to beaches farther north and in the formation of coastal "pools" that where contaminants are concentrated. In the summer months, the levels of pollution from human activities are several times higher than those allowed for swimming. Dredging of the spit and south-harbor beach to nourish the northern beaches may have been more beneficial, at only a fraction of the cost of building the groins.

In summary, considering only natural causes, the coast of Argentina is in a net erosional stage, especially from Punta Medanos (northern Buenos Aires province) to the south. The main reason for this land loss is the low rate of accretion of river sediments. In recent decades, these conditions have worsened because of reduced precipitation in the mountains and the construction of several dams across Patagonian rivers. Only the Río de la Plata keeps providing a high sediment load, although most of the time the river plume moves northward (along the Uruguay shelf) due to the Coriolis effect.

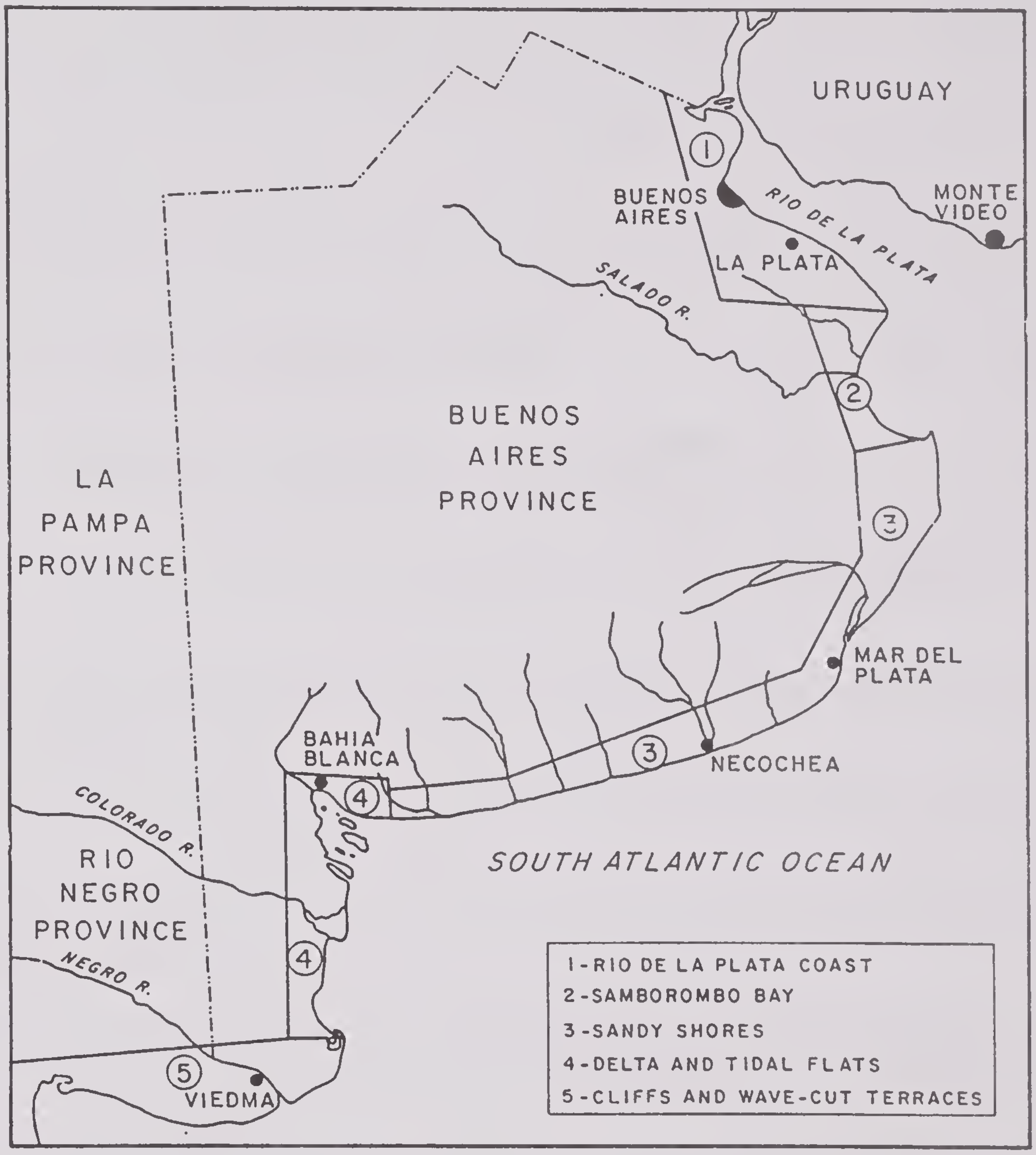
Based solely on the physical characteristics of Argentina's coastal zone, the most likely sector for developing a case study corresponds to the coast of the Buenos Aires province from the Parana River delta to the mouth of the Negro River (Figure 3). The selected shoreline has practically all types of coastal features within a manageable distance.

The study area should also include the estuaries of the Deseado and Gallego Rivers, which will be strongly affected by sea level rise. As a test site, it is also proposed to analyze the behavior of the estuary of the Santa Cruz and Chico Rivers, since because of its characteristics, it will be less vulnerable.

SOCIOECONOMIC CHARACTERISTICS

The data from the last census, taken in May 1991, are not available yet, thus compromising the accuracy required for the study of the socioeconomic characteristics of the Argentine coast. However, some preliminary assessment can be provided for Buenos Aires province and for two coastal counties from the Río Negro province directly related to the river's mouth (Table 1).

FIGURE 3. COASTAL ZONE DESIGNATED FOR THE ARGENTINE CASE STUDY



For the case study, the coastal zone has been divided into five districts related to the main geomorphological features.

The 1991 census estimated that the total population of Argentina is 32,300,000, with 40 percent concentrated within 50 km of the coastline. The littoral districts of Buenos Aires and Río Negro provinces contain almost 21 percent of the total population. The maximum population density (16 of the 21 percent) is located in Buenos Aires city and the surrounding counties, which cover only 100 km (less than 7 percent) of the provincial coast.

The population density along the country's coast rapidly reduces heading southward, except for specific urban locations, such as Mar del Plata, Necochea, Bahía Blanca, and Comodoro Rivadavía. On the Patagonian coast, there are stretches of 200 km without any urban development.

Table 1 exhibits the estimated population for the four littoral districts in Buenos Aires province, plus the district in Río Negro province. They were divided in relation to their particular physical characteristics, and their boundaries are shown in Figure 3.

The table also summarizes the main economic activities of the five districts. Except for the first district, all the others rely heavily on agricultural and cattle products. Other economic activities are typically secondary, although some industrial centers are being developed and are becoming a major input for the districts.

The largest marine harbors of the country are located within the area depicted in Figure 3. Buenos Aires harbor handles about 76 percent of the nation's exports and 92 percent of its imports. Bahía Blanca, Quequén, and Mar del Plata (in this order) all export grains, and the first two have strong exports of gas and oil derivatives, while Mar del Plata is the source of most of Argentina's fishing exports.

TABLE 1. DEMOGRAPHIC CHARACTERISTICS OF THE COASTS OF BUENOS AIRES AND RIO NEGRO PROVINCES

District Number and Name	Population[a]	Main Activities
1. Río de la Plata coast	260,000	Government, industry, commerce transport, finances, housing; export and import harbor.
2. Sanborombon Bay	60,000	Agriculture and cattle; minor industry.
3. Sandy shores	980,000	Agriculture and cattle; tourism, harbors, fisheries.
4. Delta & tidal flats	323,637	Industry, commerce, harbors, agricultural and cattle.
5. Cliffs & wave-cut terraces	52,000	Agriculture and cattle.

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[a] Population was estimated from growth projections from the 1980 census, except for district 4, which are values from the 1991 census.

INSTITUTIONAL AND LEGAL STRUCTURES

The use and management of the country's shoreline and associated waters are directed by the constitution and Civil Legislation Code. Because of the federal system, each province and county has its own particular legislation and codes governing the shoreline. In most cases, the legislation differentiates between public and private use of the coast.

Nevertheless, a general survey of the existing legislation shows that most of the provincial laws and county decrees are either overruled by national laws or in many cases are contradictory. A major issue is sand mining. Many counties forbid this activity, whereas neighboring counties allow it at different rates. As a consequence, those counties that seek some ways of preserving this natural resource are directly affected by others whose actions considerably reduce sediment transport .

An integrated, coordinated coastal management system is sorely needed in Argentina. Furthermore, there is no legislation or plans for establishing legal or institutional mechanisms for protecting against the impacts of sea level rise. Even though the federal system must respect provincial autonomy, the different political jurisdictions should develop coordinated programs based on the results of specialized studies about the impacts of sea level rise on the Argentine coast.

Simultaneously, social and cultural responses for defending the coast should be established. Public education using mass media and school systems is needed to mobilize the public to call for strong legislation and a planned strategy to protect the coast and the environment.

CONCLUSIONS AND RECOMMENDATIONS

Based on the preliminary analysis made on the available information, the working group has estimated that the region for developing the case study should be the coast of Buenos Aires province from the Parana River delta to San Antonio Bay. Other sectors of the coast that should be included in the case study are the estuaries formed by the Gallegos and Deseado Rivers in Santa Cruz province. The criteria for selecting these sectors are as follows:

- The indicated region has practically all types of coastal features common to the rest of the Argentine coast and is concentrated within only 1,500 km.
- Most of the area will be significantly affected by sea level rise, since it has the longest stretches of low-lying coasts in the country.
- The selected region has the largest concentration of inhabitants living within 10 km of the shoreline.
- The socioeconomic parameters will be largely affected by sea level rise as many agricultural, tourist, harbor, fishing, and industrial activities are concentrated along the coast of this region.
- The large number of districts along the coast apply different approaches to resolving environmental and coastal protection issues, which sometimes conflict with each other. mThis is an excellent opportunity for establishing coordinated political and socioeconomic strategies to protect against the effects of sea level rise.
- The estuary of the Santa Cruz and Chico Rivers has been selected as a test site, since it will be minimally affected by any sea level rise scenario.

INTEGRATED PROGRAM FOR COASTAL MANAGEMENT

At present, no effective effort has been made at any level in Argentina to manage the coastal zone. There have been some isolated and short-lived actions that lacked the organization and knowledge adequate to sustain themselves or to obtain further support. Although specialists in most of the oceanographic or other related disciplines work in the coastal zone, their work is normally local in scope, and not long term or interdisciplinary.

Considering that the coast is probably the most complex environment in the planet, the authors of this paper proposed to both the Argentine Science Secretary and the United Nations Development Programme establishing a coordinated system for coastal management. They have proposed that the Integrated Program for Coastal Management will coordinate all research being done in the coastal zone of Argentina, without imposing any restrictions on the individual or group of researchers. The idea in this case is actually to combine the present and future expertise of those researchers, plus the instrumentation and data available to obtain integrated results based on multi- and interdisciplinary approaches.

The proposed program will also develop a national GIS-based data base system with information available to users in research, administration, industry, etc. Within the program, a specific legal, socioeconomic, and cultural department will be able to asssit all levels of government officials, legislators, and agencies, but also will be responsive to private industry, business, and the general public.

EXTERNAL ASSISTANCE

To develop the proposed case study and also to establish an ongoing coastal management system, Argentina needs external assistance from the countries and specialists who have extensive experience in coastal management. Technical assessments to establish the coordinating program, as well as the data base system and the legal department, are required within a very short time frame. Argentina's economic status only allows for reduced grants that are no enough to cover the minimum expenses of such an ambitious but necessary program. Therefore, external economic support is considered as critical to the success of this project.

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IMPACTS OF SEA LEVEL RISE ON THE COAST OF ARGENTINA

Enrique J. Schnack
Laboratorio de Oceanografia Costera
Facultad de Ciencias Naturales y Museo
La Plata, Argentina

Karen Clemens Dennis and
Robert J. Nicholls
Laboratory for Coastal Research
University of Maryland
College Park, Maryland

Felix H. Mouzo
Independent Consultant
Buenos Aires, Argentina

ABSTRACT

A 1-meter rise in sea level would erode or inundate at least 2,000 km^2 of land in Argentina, which is comprised mainly of wetlands. However, erosion would have the biggest impact on the population, possibly claiming land and structures with a value of about $5 billion. The damage would be particularly severe in and around the capital city of Buenos Aires.

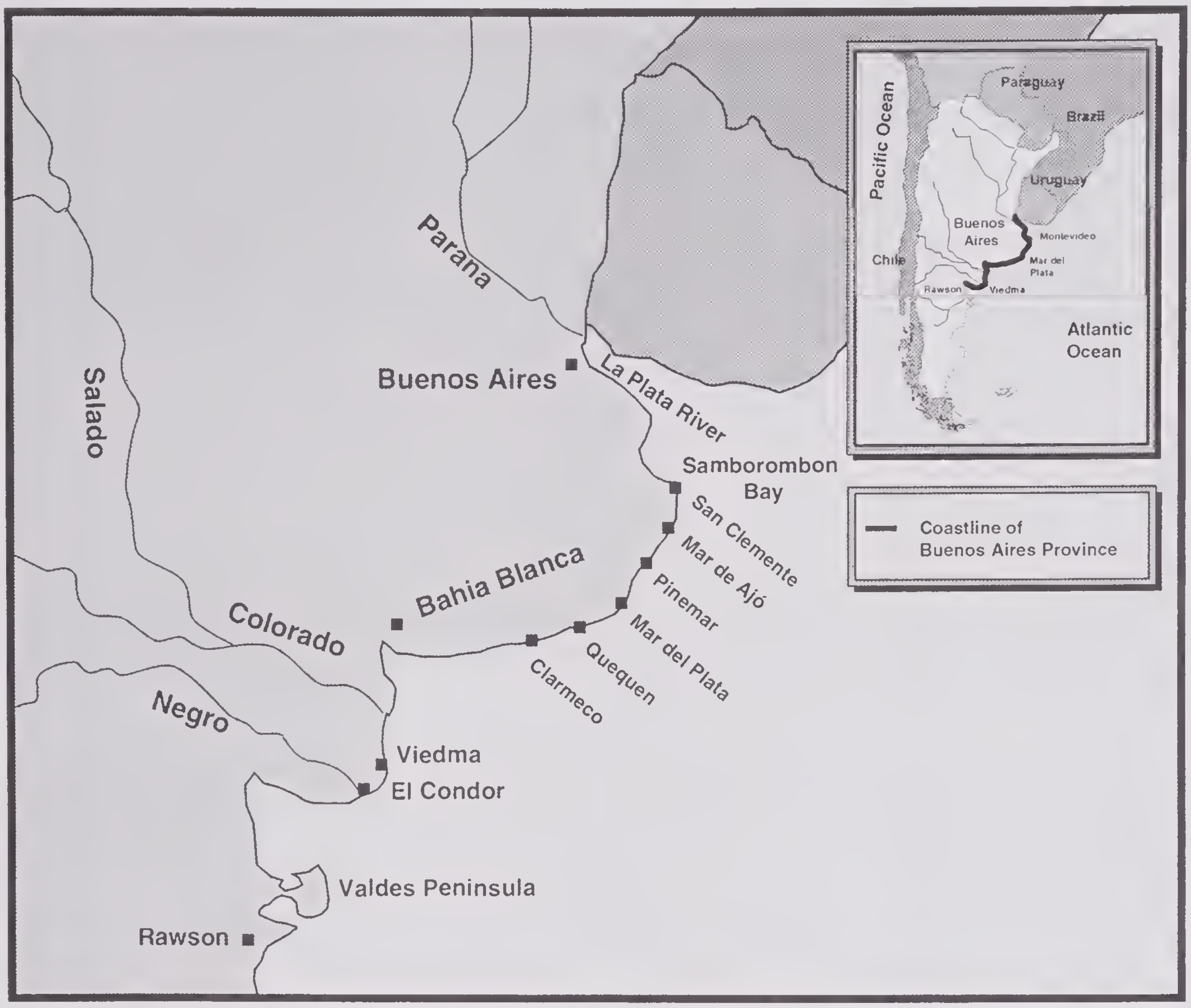
Protecting the developed shoreline against a 1-meter rise would cost $550 to $1,300 million (1991 U.S.), of which more than 50 percent would be devoted to beach nourishment. Assuming that this investment occurred over 50 years (2051 to 2100), it would represent an annual undiscounted cost of 0.2 to 0.4 percent of the national gross investment in 1987. Future work is required for the Parana delta and for drainage problems in the low Pampas by Samborombon Bay. A national assessment and a comprehensive coastal zone management strategy are recommended to reduce Argentina's vulnerability to sea level rise.

THE STUDY AREA

The Argentine coastline consists of five provinces and one federal district. In this study we analyzed the impacts of accelerated sea level rise on the northern half of the Argentine coastline, including the federal district of Buenos Aires, Buenos Aires Province, Río Negro Province, and one-quarter of Chubut Province. The Buenos Aires Province coastline consists of the Parana Delta (which also extends into Entre Ríos Province), the muddy coastline along the south bank of the La Plata River, the extensive wetlands adjacent to the Samborombon Bay, the sand beaches along the Atlantic Coast from San Clemente to Bahía Blanca (these include some erodible cliffs and the quartzite headland at Mar del Plata), and the wetlands from Bahía Blanca to Bahía San Blas (Figure 1).

Buenos Aires Province is the most important coastal province of Argentina. It has more than 1,500 kilometers of coastline and nearly 12 million people, or 40 percent of the national population (Schnack et al., 1990). The average population density for the province is 35.3 people/km^2. Ninety percent of the people in Buenos Aires Province live in urban centers, the largest of which are on the coast. These centers include Buenos Aires City (together with its suburbs, greater Buenos Aires, 10 million inhabitants), La Plata (460,000 inhabitants), Mar del Plata (410,000 inhabitants), and Bahía Blanca (220,000 inhabitants).

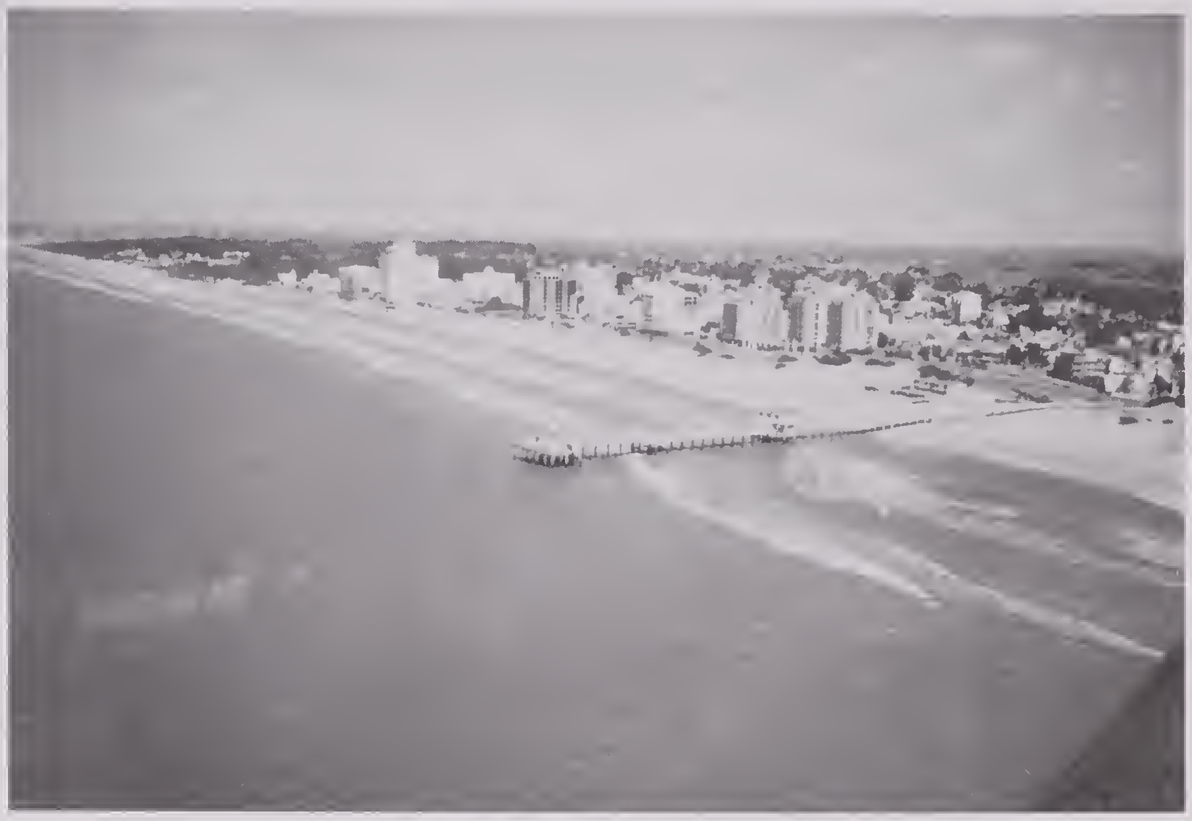
FIGURE 1. ARGENTINA: BUENOS AIRES PROVINCE AND NORTH PATAGONIAN COAST



Besides containing the largest coastal urban centers in the country, Buenos Aires Province is the site of four of the main harbors in Argentina (Buenos Aires Harbor, Mar del Plata Harbor, Quequén and Necochea Harbors, and Bahía Blanca Harbor). Economic activities at these harbors include chemical, textile, metallurgical, food, and fishing industries; packing houses; agricultural and cattle-raising activities; and petrochemical industries. Buenos Aires Province also has the majority of the coastal tourist resorts (Figures 2 and 3).

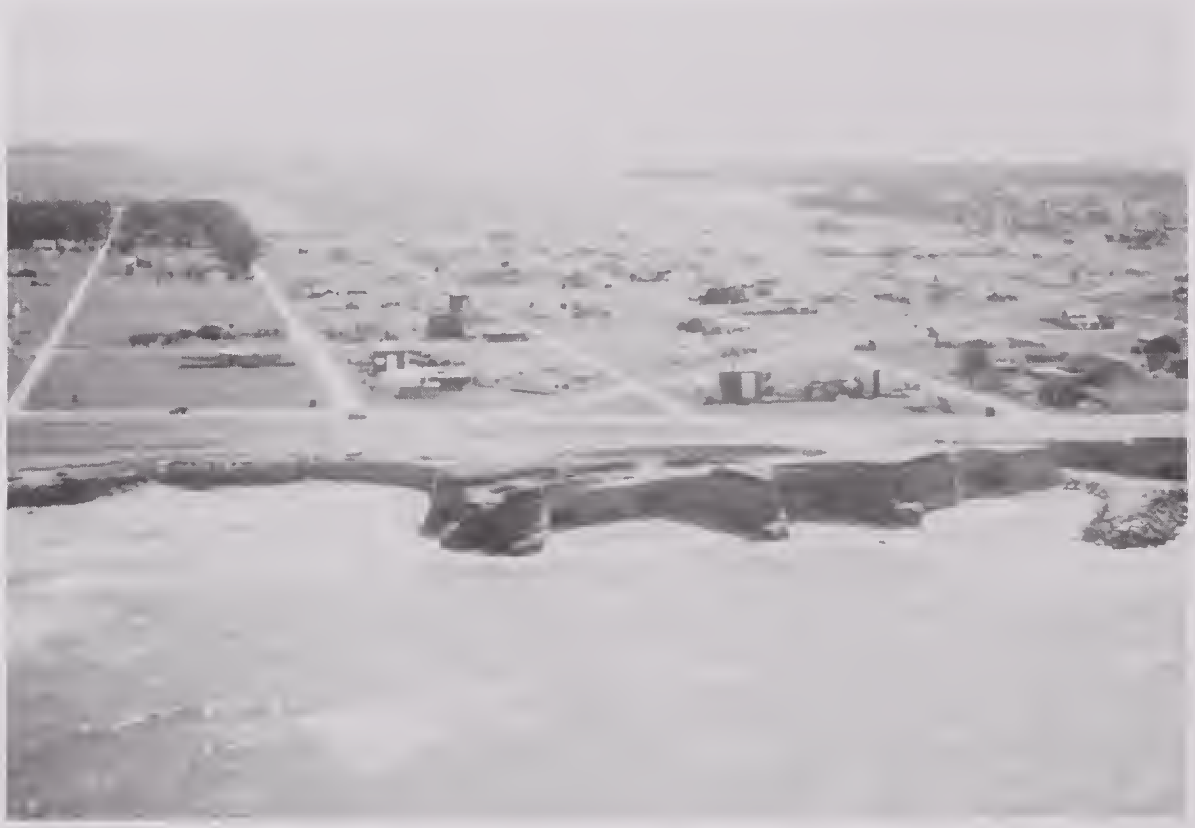
The coastlines of Río Negro Province and the northern quarter of Chubut Province are composed of mixed sand and pebble beaches and erodible cliffs from Bahía San Blas to just south of San Antonio Oeste, and high erodible cliffs (>100 meters) with some pocket beaches south of San Antonio Oeste to Rawson just south of the Valdes Peninsula. The average population densities for these two provinces are low: only 1.9 and 1.2, people/km^2, respectively (Ejército Argentino, Instituto Geográfico Militar, 1989). Río Negro Province has a few medium to small tourist areas (including Balneario El Condor and Las Grutas), one urban center with fewer than 10,000 inhabitants (San Antonio Oeste), and two small ports (San Antonio Este and Punta Colorado). The high erodible cliffs of the northern quarter of the Chubut Province are topped with flat, arid land that is used mostly for sheep grazing (Figure 4). This area contains one major harbor (Puerto Madryn) and one small tourist area (Playa Unión).

FIGURE 2. SANTA TERESITA BEACH, BUENOS AIRES PROVINCE



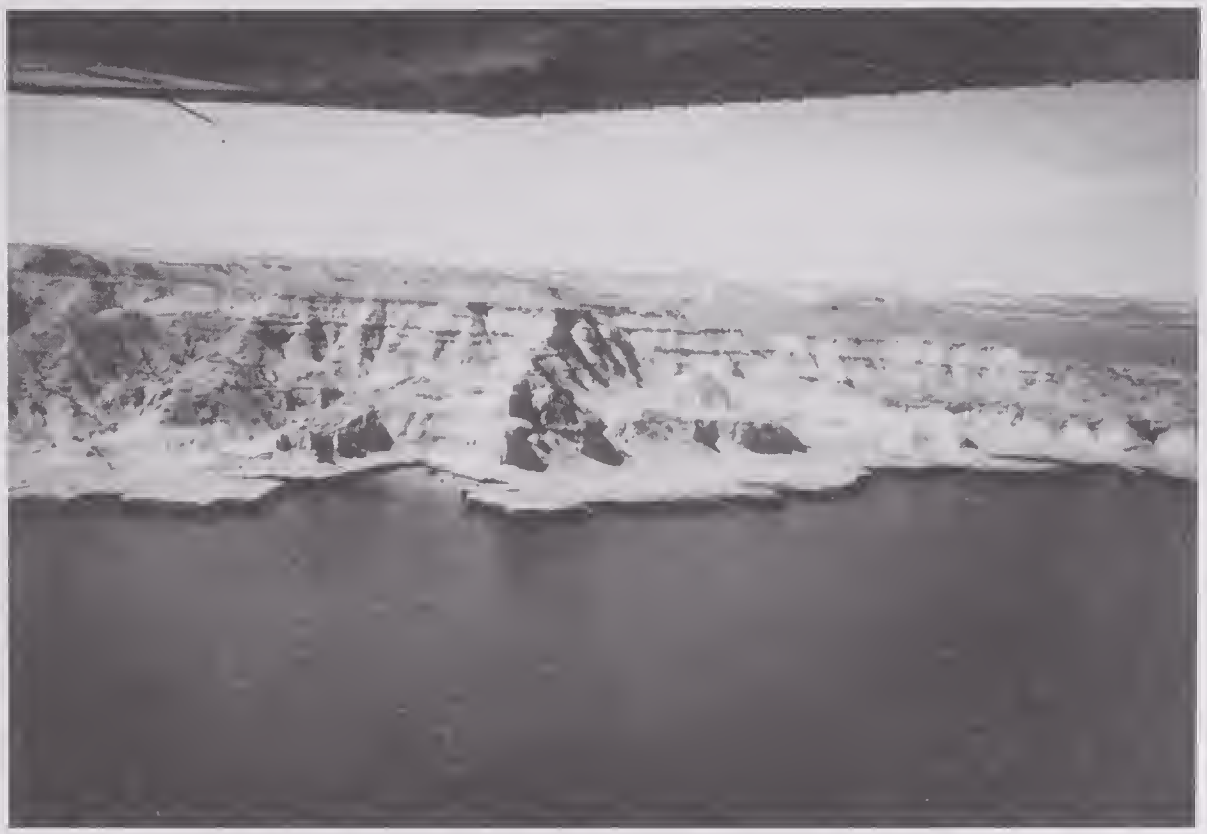
This oblique view of Santa Teresita Beach shows the typical urbanization of the sandy shorelines of Buenos Aires Province.

FIGURE 3. EROSIVE COASTLINE IN THE PROVINCE OF BUENOS AIRES



This photograph shot north of Mar del Plata in Buenos Aires Province shows erosive coastline carved in Pleistocene sediments.

FIGURE 4. TYPICAL VIEW OF THE PATAGONIAN COASTLINE



This oblique air view of south of Peninsula Valdés in Chubut Province is typical of the Patagonian coastline. Although sea level rise may erode these cliffs, there will be very limited human impact.

ANALYTICAL METHODS

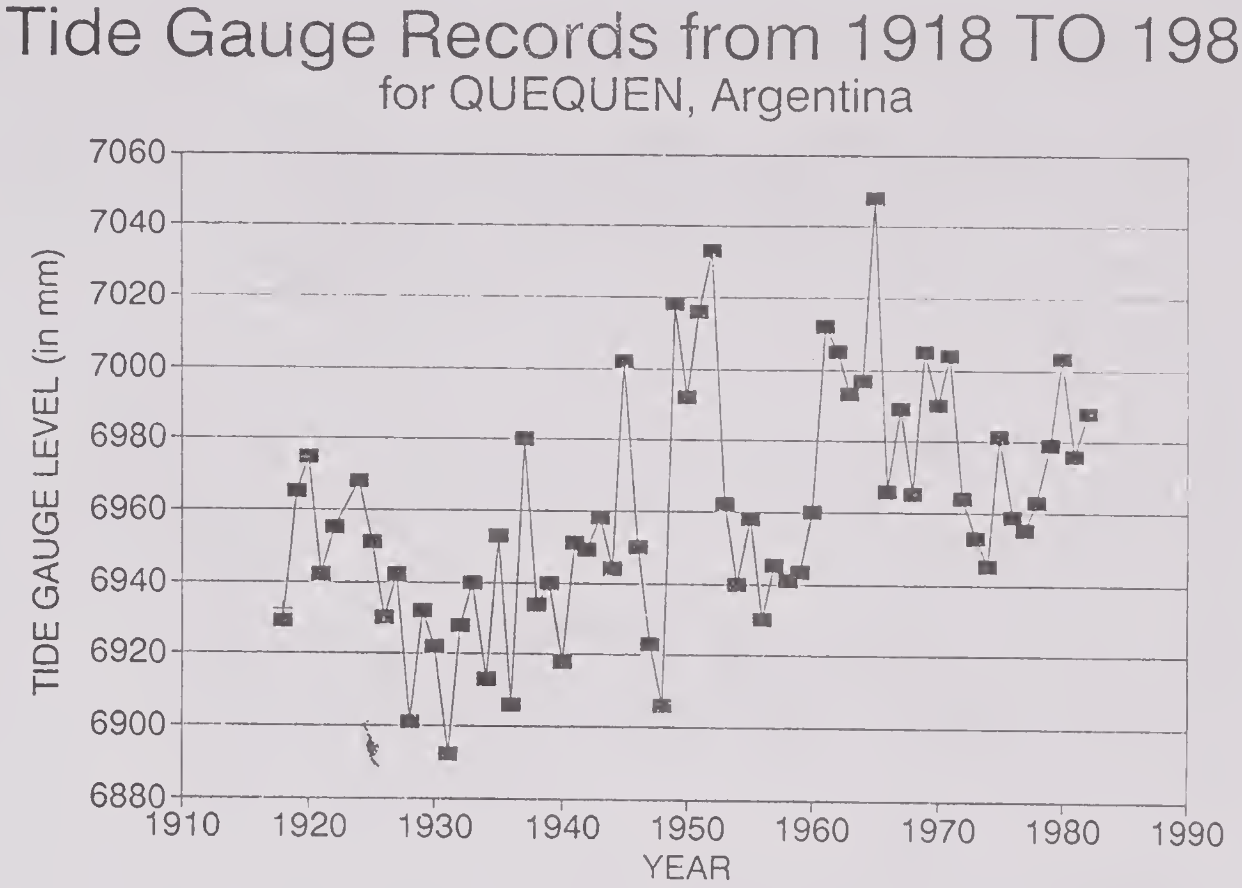
We initiated a study of the impacts and possible responses to sea level rise for the northern half of the Argentine coast. This study quantifies: (1) the land lost due to sea level rise; (2) the economic value of that land; and (3) the cost of protecting that land.

SEA LEVEL RISE SCENARIOS

We used four arbitrary scenarios of eustatic (or worldwide) sea level rise: 0.2 (the baseline, after Douglas, 1991), 0.5, 1.0, and 2.0 meters by the year 2100. These scenarios need to be converted into relative (or local) sea level rise scenarios. Relative sea level rise is a combination of eustatic changes and any uplift/subsidence of the land.

To examine this effect, we obtained tidal gauge records for nine stations in our study area from the Permanent Service for Mean Sea Level (PSMSL). Only two of these stations were appropriate for a mean sea level analysis: Quequén and Buenos Aires (Figure 1). Quequén has 64 years of record, from 1918 to 1982 (Figure 5). A simple regression of the data gives an annual sea level rise of 0.8 mm/yr. This is slightly lower than the worldwide eustatic sea level trend of 1 to 2 mm/yr (IPCC, 1990a). Others have analyzed these data and have found differing results. Lanfredi et al. (1988) obtained a sea level rise of 1.6 mm/yr. This is mainly due to their filtering procedure, which removed the first and last eight records in the series (Figure 5). In contrast, Emery and Aubrey (1991) found a sea level drop of 0.8 mm/year at Quequén; however, they inexplicably only use the data from 1968 to 1982.

FIGURE 5. TIME SERIES OF MEAN SEA LEVEL AT QUEQUÉN: 1918–1982



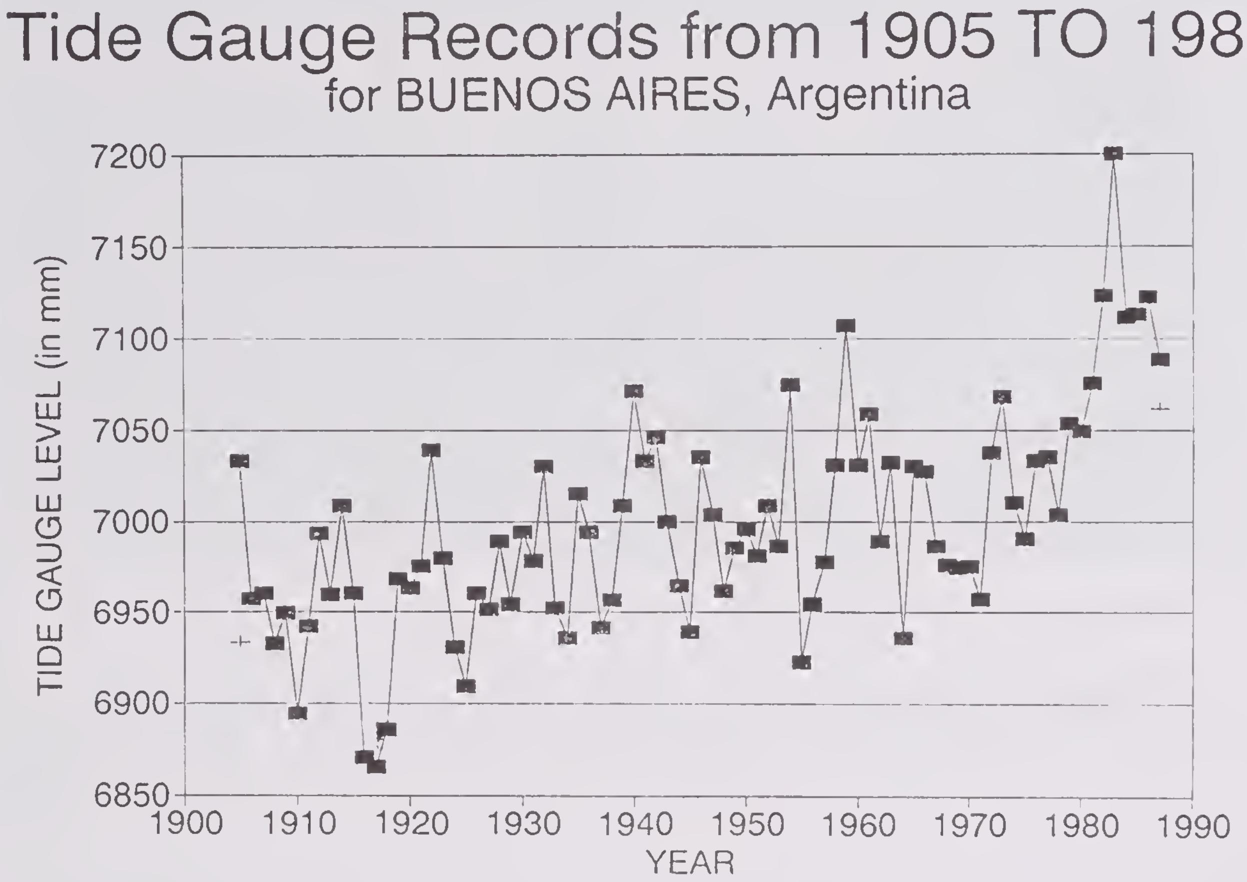
Buenos Aires has data from 1905 to 1987 (Figure 6), and regression gives a sea level rise of 1.6 mm/yr. However, the PSMSL states that this station has been affected by noticeable meteorological influences. Thus, all the data available indicate a stable coastline, with present sea level rise being within the accepted range of eustatic sea level rise. Therefore, for all practical purposes, eustatic scenarios of 0.2, 0.5, 1.0, and 2.0 meters can be converted directly to relative sea level rise scenarios.

FIELD WORK

One of the major problems with studying the impacts of sea level rise in developing countries is the lack of detailed information on coastal elevations. Some areas of Argentina have maps with contours as small as 1.25 meters; however, other areas have almost no coverage at all. Because of the large size of Argentina and the rapidity of coastal development, it is hard to obtain updated information on the size of coastal towns and the number of structures located near the coast. Therefore, we applied aerial videotape-assisted vulnerability analysis, as described by Niang et al. (these proceedings) to give us information on relief and coastal land use and development.

We videotaped the coastline of the northern and central two-thirds of the country (2100 km) at an altitude of 60 to 75 meters and an air speed of approximately 165 km/hr. After finishing the flight in Trelew (near Rawson—Figure 1), we performed ground truthing to collect information on a number of factors, including coastal topography and geomorphology, land values, structure values, shipping in and out of harbors, fish catch statistics, and general economics. We visited all the major coastal towns and tourist resorts between Rawson and Buenos Aires when returning to the north. Also, we surveyed eleven representative topographic profiles, three of which were connected to known benchmark elevations. In addition, we used nine cross-shore profiles along the marshy Samborombon Bay coast.

FIGURE 6. TIME SERIES OF MEAN SEA LEVEL AT BUENOS AIRES: 1905–1987



LAND LOSS ESTIMATES

EROSION

The Bruun Rule is much used to calculate erosion due to sea level rise. An adapted version of this approach, as described by Niang et al. in these proceedings, was used here. The depth of closure is the variable in the Bruun Rule equation that is the most difficult to estimate. For our calculations, we used two closure depths (d_{L1} and d_{L100}), giving us a low and a high estimate of shoreline recession.

Wave measurements are available from Mar de Ajó and Pinamar (Massonneau et al., 1981), which are located between San Clemente and Mar del Plata (Figure 1); and from Balneario El Condor (Colado et al., 1981), which is located at the mouth of the Río Negro (Figure 1). The wave data for Pinamar are continuous and include the months of October 1979 through September 1980, while the wave data for Mar de Ajó have many gaps and includes the months of November 1979 through October 1980. The wave data for Balneario El Condor include the months of December 1985 through June 1986, with some missing data for December 1985 and March 1986. We examined the Mar de Ajó and El Condor data relative to Pinamar, and have determined that there is no apparent bias in wave height caused by the gaps in the Mar de Ajó and El Condor stations.

Hence, we calculated d_{L1} and d_{L100} for Mar de Ajó, Pinamar, and Balneario El Condor (Table 1). These depths of closure are inappropriate for the entire coast, as there is variable shelter from waves. Therefore, using expert judgment, we used the depths of closure, as given in Table 2.

TABLE 1. CALCULATED DEPTHS OF CLOSURE (METERS)

Location	d_{L1}	d_{L100}
Mar del Ajó	3.2	5.6
Pinamar	5.8	10.1
Balneario El Condor	3.6	6.3

TABLE 2. DEPTHS OF CLOSURE USED IN THIS STUDY (METERS)

Location	d_{L1}	d_{L100}
San Clemente to Punta Medanos	3.2	5.6
Punta Medanos to Claromeco	5.8	10.1
Claromeco to Sauce Grande	4.0	7.0
Sauce Grande to San Blas	3.0	5.3
San Blas to Promontorio Belén	3.6	6.3
Golfo San Matías, San José and Nuevo	3.0	5.3
Peninsula Valdés (Ocean Coast) to Rawson	3.6	6.3

We determined the active profile width (from d_{L1} and d_{L100}, respectively) on navigation charts by measuring to the first contour (usually the 5- or 1-meter contour) and linearly interpolating the actual distance. The d_{L1} and d_{L100} depths were referenced to a datum 1 meter above mean low water (Niang et al., these proceedings).

Buenos Aires Province

The geomorphology of the northern part of the Buenos Aires Province coastline, from San Clemente to Mar del Plata is very uniform. For the Bruun Rule calculations, we split this coastline into two segments where the depth of closure changes (Punta Medanos).

From Mar del Plata to Bahía Blanca there are some variations in the coastline, including some cliff areas. We split the coastline into similar sections and followed the same procedure as in the previous section. Except for the city of Mar del Plata, which is located on quartzite cliffs, the cliff areas in this section of coastline are variable in elevation (approximately 5 to 25 meters) and are composed of semi-consolidated silts with subordinate sand and clay fractions, and calcretes of Plio-Pleistocene age (Schnack, 1985). In these areas, we assumed that the cliffs would also follow an equilibrium model with sea level rise. Thus, we applied the same concept as the Bruun Rule to estimate cliff retreat, resulting in minimum recession estimates.

The final two sections of the Buenos Aires coastline include the marshes from Bahía Blanca to the Río Negro and the area along the La Plata River, from Buenos Aires to the Atlantic Ocean. Inundation would be the main impact of sea level rise in the marshes of Bahía Blanca to Río

Negro (see next section). For the sections of sandy coastline in this area, we made Bruun Rule estimates, described above. For the La Plata coastline, we could not estimate a depth of closure, since we did not have any wave data. Also, this section of coastline is relatively sheltered and composed of muddy, rather than sandy, sediments. Consequently, the Bruun Rule is not applicable.

As a first estimate, we used an equilibrium approach similar to the Bruun Rule. We estimated depth of closure at 4 meters depth using nearshore morphology—either a break in slope off the coastline or the deepest point where the depth contours are parallel to the shore. We then applied the equilibrium approach, assuming conservation of sediment. Consequently, these are minimum erosion rates. Inundation would be the main impact of sea level rise just southeast of Buenos Aires and around Samborombon Bay where there is an extensive marsh system.

Río Negro and Chubut Provinces

The Río Negro and one-quarter of the Chubut Provinces are composed of a mixture of sandy coastlines, low cliffs (5 to 25 meters), and extremely high cliffs (more than 100 meters). The sections of sandy coastline were treated as in Buenos Aires Province, and Bruun Rule retreats were estimated. Retreat was only estimated in the low cliff areas if the land on top of the cliff was economically valuable (used for development or agriculture). No land loss was calculated for the high cliff areas, since the retreat would probably be relatively small due to the height of the cliffs, and the land on top of the high cliffs is used mainly for sheep grazing and has very low value.

INUNDATION

To assess the land lost from inundation, we combined the information from topographic maps, the video record, and in the case of Samborombon Bay, nine profiles through the wetlands. Using this information, we plotted the 2-meter contour (above mean high water) on the topographic maps. We then interpolated the land loss for 0.2, 0.5, and 1.0 meters of sea level rise, since the information that we have is not detailed enough to plot these contours. In the city of Buenos Aires, the lowest available contour was 5 meters (above mean sea level), so we estimated the land loss for 0.2, 0.5, 1.0, and 2.0 meters of sea level rise by combining information obtained on the videos and interpolation.

These calculations do not take into account the possibility of sedimentation in the inundated area. In the case of the wetland areas (adjacent to Samborombon Bay and the wetlands south of Bahía Blanca), there is little sediment coming into the wetland system from inland sources. In the case of Samborombon Bay wetlands, the gradient of land is so shallow that next to no sediment can travel from the inland to the coast. In the case of the wetlands south of Bahía Blanca, one is adjacent to the Colorado River and the other is adjacent to the Río Negro. Both of these rivers no longer carry much sediment to the coast, since they both have dams upstream. Therefore, the major source of sediment would be the neighboring coast (cf. Stive et al., 1990). It is not known how great this source is, so it was assumed to be minor. The areas inland of the wetlands were analyzed on the topographic maps to ascertain how much area would be converted from dryland to wetland.

Another area that may be inundated, or at least may have significantly increased drainage problems from accelerated sea level rise, is the coastal plain of the Salado Basin, a low-lying portion of the Pampas in Buenos Aires Province, which extends inland from the Samborombon Bay wetlands. This area is mainly used for cattle grazing. At present, there are drainage problems in the Pampas after rain storms. To try to improve the drainage, canals have been dredged to the coast through the Samborombon Bay wetland. The canals have not been completely successful and will be less so with accelerated sea level rise. A separate project was initiated to assess the increased drainage problems due to sea level rise, and this will be discussed in a future report.

COSTS OF PROTECTION

Protecting Argentina from sea level rise has been broken down into four possible scenarios (see also Niang et al, these proceedings):

1. *No Protection.*

2. *Present Protection.* Existing protection, including harbors, is maintained.

3. *Protection of Important Areas.* Medium to highly developed areas, plus strategic areas (as assessed by the videotape and other sources), are protected (e.g., cities, tourist beaches, factories).

4. *Total Protection.* All coastal areas with a population greater than 10 people/km^2 are protected (IPCC, 1990b).

NO PROTECTION CASE

Assumes there is no protection (any protection that already exists is not considered).

EXISTING PROTECTION CASE

The only areas presently protected along the coastline of Argentina are some of the major harbors and portions of the Buenos Aires coastline. This includes the harbors of Buenos Aires, Mar del Plata, Quequén, and Bahía Blanca. These areas are protected by the nature of their harbor facilities. Other than the harbors, some of the tourist towns have a small cement wall at the coast that is used as a promenade. The areas with promenades were not included as protected coastlines.

We did not have enough information to calculate the cost of protecting the harbors, so we used the national harbor costs for Argentina from the Intergovernmental Panel on Climate Change (IPCC, 1990b). This is $262 million for a 1-meter scenario. For the 0.5- and 2.0-meter scenarios, we adjusted the cost linearly. The baseline scenario of 0.2 meter of sea level rise was not evaluated.

PROTECTION OF IMPORTANT AREAS

We measured the length of the coastline with medium to high development (from the videos), where towns, factories, and tourist areas are located close enough to the coastline to suffer structural damage from sea level rise. Medium to high development is defined as any area where 15 percent of the ground is covered by structures. In Argentina, these include mostly tourist towns, harbors, and some towns and cities. We then assumed that tourist towns, where beaches are economically important, would be protected by beach nourishment, and the rest of the "important areas" would be protected by sea walls.

The cost of beach nourishment was determined using similar assumptions to Bruun Rule shoreline recession calculations. To stop longshore loss of the beach fill (sand), large terminal groins were used, as explained in Niang et al. (these proceedings).

We also developed a series of sea wall designs, whose application depends upon wave environment. These include a sheltered-coast sea wall, a low- and high-cost design for open (wave-exposed) coasts, (Niang et al., these proceedings), and in the case of Argentina, a sea wall for cliff protection. This sea wall design is the same as the high-cost estimate for the sandy coast ,except that it includes a 20-meter-wide platform from the top of the sea wall to the cliff face. The area between the sea wall, the cliff face, and the ground is filled with material at a cost of $5 per cubic meter. The costs of reprofiling the cliff or stabilization with other procedures (such as geotextiles) are not considered.

We divided the sandy coastline into three sections based on wave data. The wave data for Mar de Ajó are used for the area from San Clemente to Punta Medanos, the wave data for Pinamar are used from Punta Medanos to Bahía Blanca, and the wave data from Balneario El Condor are used south of Bahía Blanca. Table 3 presents the sea wall unit costs used in this study.

TABLE 3. UNIT COSTS OF SEA WALLS (KM)
(MILLIONS OF 1991 U.S. DOLLARS)

Sea Wall Type	**Sea Level Rise (m)**		
	0.5	*1.0*	*2.0*
Sheltered Coast	$0.12	$0.33	$1.07
LCOC	0.16	0.44	1.35
HCOC (Mar de Ajó)	1.20	1.50	2.31
HCOC (Pinamar)	1.43	1.72	2.54
HCOC (El Condor)	0.84	1.13	1.95
HCCC (Mar del Ajó)	2.78	3.84	6.07
HCCC (Pinamar)	3.25	4.31	6.56
HCCC (El Condor)	2.09	3.13	5.34

LCOC —Low Cost Open Coast.
HCOC —High Cost Open Coast.
HCCC —High Cost Cliff Coast.

TOTAL PROTECTION

This case protects all areas with an average population exceeding 10 people/km^2. In the case of Argentina, this includes Buenos Aires Province, with a population of 35.1 people/km^2, and the provinces Entre Ríos and Santa Fe in the Parana delta, with 11.5 and 18.5 people/km^2, respectively (Ejército Argentino, Instituto Geográfico Militar, 1989). For this study we included protection of Buenos Aires Province and all of the towns in Río Negro and Chubut Provinces that we have protected in the important areas protected case. The protection of the Parana delta is a separate study and will be discussed in a future report. For this case, we protected the coastline along the La Plata River, including the land adjacent to the wetlands in Samborombon Bay with the sheltered-coast sea wall, the beaches along the Atlantic Ocean with the low- and high-estimate open-ocean sea wall, the cliffs along the Atlantic Ocean with the cliffed-coast sea wall, and the land adjacent to the mud flats and wetland areas around and south of Bahía Blanca with the sheltered-coast sea wall. To obtain the total protection cost, we added the cost of the important areas protected case to the cost of protecting the rest of the coastline.

ECONOMIC VALUE OF LAND LOST

To estimate the economic value of the land lost, we viewed the videotapes and recorded the coastline lengths of developed areas, including towns, cities, tourist areas, and agricultural areas. We then estimated the distance that the developed areas extended inland from the coast and the percent concentration of structures and crop land in that area. We then determined the extent of the developed area that would be lost with each sea level rise scenario.

For the case of structures, this area was multiplied by the percent concentration to give a total area of structures affected. We then divided the total area by estimates of the size of each type of structure, giving us a total number of structures affected. We calculated the value of these structures by assuming a value for each type of structure and multiplying it by the number of structures identified. The numbers assumed for structure size were based on making an approximate estimate from the video. The structure values were found by interviewing real estate agents in each of the towns along the coast. The value of farmland was also ascertained by interviewing real estate agents in each area. The values of high-rise buildings were based on average size and were adjusted according to the value of houses in the area. Table 4 shows the values used for houses, high rises, and farmland along the Argentine coastline.

TABLE 4. VALUES USED FOR HOUSES, HIGH RISES, AND FARMLAND ALONG THE ARGENTINE COAST (1991 U.S. DOLLARS)

Area	**House Value** (per building)	**High-Rise Value** (per building)	**Farmland Value** (per hectare)
All areas (except where specified below)	$25,000	$600,000	$500
Pinamar	40,000	1,000,000	500
Mar Chiquita	18,000	N/A	500
Quequén and Necochea	35,000	600,000	500
Mt. Hermoso	35,000	600,000	500
Farm or Fishing Houses	10,000	N/A	N/A
Farmland South of San Blas	N/A	N/A	250
San Antonio Este	15,000	N/A	250
San Antonio Oeste	10,000	N/A	250
Small Fishing Camp Houses	2,000	N/A	N/A
Madryn	50,000	1,000,000	N/A
Playa Unión	15,000	N/A	N/A
Small houses South of Playa Unión	5,000	N/A	N/A

For the city of Buenos Aires and its suburbs, average values of land and structures were obtained by consulting with local real estate agents. The construction along the Riachuelo River was assumed to have a value of $30,000 per 400 square meters, and the area along the La Plata River, near the harbor, was assumed to have a value of $1,000,000 per 400 square meters.

Results

Geographic Distribution of Impacts

Sea level rise will have very little impact on the coastline south of Buenos Aires Province, except for a few low-lying urban and harbor areas. Impacts between Trelew and Tierra del Fuego (the south of the country) appear to be relatively small based on the coastal geomorphology and the low level of coastal development. Therefore, the major impacts of accelerated sea level rise along the Argentine coastline will be concentrated in the Buenos Aires Province area.

The impacts on Buenos Aires Province will be significant, since the majority of the population and highly valued real estate are along the coastline. Although Buenos Aires City itself is located on fairly high land, most of the erosion and inundation occur on the recently accreted land along the La Plata River. Some of the urban structures located on this low-lying land are an airport, the soccer stadium, and the university. Even though only a small section of the central part of the city would be lost, land values are very high. Thus, the economic loss would be significant.

From Buenos Aires to Punta Piedras (the beginning of Samborombon Bay, where a large wetland area begins), farmland and coastal towns will be eroded and flooded. Adjacent to Samborombon Bay, the extensive wetland system (approximately 500 km^2) may be partly inundated by accelerated sea level rise, damaging the local and regional fisheries that depend on the marsh for juvenile stages. The large area of land inland from the Samborombon wetlands, part of the Pampas, is extensively used for cattle grazing. Accelerated sea level rise would increase flooding of this land, which could have a major impact on the cattle industry in this area. Protection of this land would be costly and would involve dikes and improved drainage. (A detailed study of the impact of sea level rise on this Pampas sector will be published in a separate report.)

The highest concentration of coastal tourism is along the coastline from San Clemente to Mar del Plata, since this area is the most easily accessible to Buenos Aires. This is a sandy coastline with an extensive dune system (between approximately 150 and 1,200 meters wide). Accelerated sea level rise would erode the sandy coastlines, causing great economic losses in the developed areas. It could also cause saltwater intrusion into the freshwater aquifer that is located in the dune system. Mar del Plata, the largest urban area on the Atlantic coastline and an important tourist area would not be in danger from accelerated sea level rise, since it is constructed on quartzite cliffs that are next to the sea. However, its beaches, which are necessary for tourism in the area, would be lost unless they were nourished, and the port, which is one of Argentina's main harbors, would have to be upgraded.

North and south of Mar del Plata, the coastline is composed of erodible cliffs with a coastal road and developments on top of which would be affected by sea level rise. Southwest of Mar del Plata to Bahía Blanca, farmland, a major port, and some tourist towns would be affected by sea level rise. Finally, in the southernmost section of the Buenos Aires Province coastline, the wetlands and tidal flats surrounding and to the south of Bahía Blanca would be inundated by accelerated sea level rise. There would also be major impacts on the ports around Bahía Blanca, where the infrastructure and the developments associated with the ports are located essentially at the present high-tide level on reclaimed land.

ECONOMIC AND LAND LOSSES

Table 5 illustrates the amount of land lost from erosion of the sandy, cliffed, and muddy coastlines, and inundation of the wetlands and portions of the muddy coastline. Despite the apparently small magnitude of erosion, it would have the largest effect on the population. This is because most of the cities, towns, and tourist areas are located on the sandy and muddy coastlines, which are subject to erosion.

TABLE 5. NO PROTECTION CASE: TOTAL LAND LOST TO EROSION OF DIFFERENT SHORELINE TYPES (KM^2)

Land Type	**Sea Level Rise (m)**			
	0.2	*0.5*	*1.0*	*2.0*
Sandy Coast	11- 23	27- 56	55- 113	110- 225
Developed Cliff Coast	0.5-1.4	1.4-3.5	2.7-7.0	5.4-14.0
Muddy Coast	46	118	328	655
Wetlands	0	811	1,623	3,245
Total	**58-70**	**958-990**	**2,009-2,071**	**4,015-5,033**

This table also shows that large areas of low-lying land in the wetlands and along the muddy coast will be inundated. Inundation will mostly occur in the wetland areas of Argentina, including the wetlands adjacent to Samborombon Bay, and the two large wetlands south of Bahía Blanca. We have assumed that no wetlands will be lost in the baseline scenario, since wetland loss is not currently reported to be a problem. Therefore, we conclude that enough sediment is feeding the wetlands to allow them to keep pace with present (baseline) sea level rise.

Inundation will also occur in the city of Buenos Aires and southeast of the city in mostly grazing and agricultural land. There will also be major inundation in the Parana delta, which is located mainly in the Entre Ríos Province (a separate project, which will be described in another report).

NO PROTECTION

In this case, all of the land listed in Table 5, and the economic value of that land along with the structures located on it would be lost (Table 6). For the 1-meter scenario, land loss includes about 2,000 km^2, and economic losses range from $5.1 billion to $5.5 billion. The largest percent of the losses would be in and around Buenos Aires City, since property values are so high there. However, there would also be a significant impact on the coastline from San Clemente to Mar del Plata, where the majority of the tourist resort towns are located. We have not considered the economic losses due to impacts on the nation's harbors.

PRESENT PROTECTION

Existing protection is mainly located in harbors and along some of the Buenos Aires City coastline. This option would have little effect on the amount of land lost, since most of the land lost is in the wetlands and along the muddy coast. However, it would have a large impact on economic value lost, since some of the highest-value real estate is located in Buenos Aires and in other harbor areas.

TABLE 6. NO PROTECTION CASE: ECONOMIC VALUE LOST ON THE OPEN-OCEAN CLIFFED AND SANDY COASTLINES[1] ON THE LA PLATA RIVER, AND TOTALED AND COMPARED TO GNP[2] (MILLIONS OF 1991 U.S. DOLLARS AND 1991 GNP)

Land Type	**Sea Level Rise (m)**			
	0.2	*0.5*	*1.0*	*2.0*
Open Ocean	$48-137	$193-417	$312-746	$722-1,119
La Plata River	1,204	2,396	4,775	9,529
Total	**1,251-1,340**	**2,589-2,814**	**5,087-5,521**	**10,251-10,648**
%GNP	1.8 - 2.0	3.8 - 4.1	7.4 - 8.1	15.0-15.6

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[1] Excluding Bahía Blanca.

[2] Source: PC Globe, 1992.

PROTECTION OF IMPORTANT AREAS

Under this protection option, most of the land (1,991–2,049 km^2 for the 1-meter scenario) would still be lost, since the majority of the land lost is due to inundation of unpopulated wetlands and areas along the coast of the La Plata (Table 7). This option would protect developed areas, reducing economic value lost by 99 percent to $54.8–$70.9 million for the 1-meter scenario (Table 8). The economic value lost under this option includes less densely developed land (less than 15 percent of the ground covered by structures) and farmland.

TABLE 7. LAND LOSS: IMPORTANT AREAS PROTECTED AND TOTAL PROTECTION CASES (KM^2)

Rise (m)	**Important Areas Protected**	**Total Protection**
0.2	54 - 65	1- 5
0.5	946 - 976	814 - 822
1.0	1,991- 2,049	1,629 - 1,645
2.0	3,980 - 4,096	3,257- 3,289

TABLE 8. TOTAL ECONOMIC VALUE LOST: IMPORTANT AREAS PROTECTED AND TOTAL PROTECTION CASE (MILLIONS OF 1991 U.S. DOLLARS)

Rise (m)	**Important Areas Protected**	**Total Protection**
0.2	$20.4 - 23.9	$0.34 - 1.1
0.5	36.1- 41.0	0.85- 1.9
1.0	54.8- 70.9	1.0 - 3.5
2.0	84.2- 103.4	1.6 - 4.7

COSTS OF PROTECTION

Under all the protection options, large areas of wetlands would be lost, with uncertain environmental and coastal resource implications. Following are the costs of each protection option.

NO PROTECTION

The cost in manpower and materials of not protecting the coastline would be zero. However, there would be large losses of structures and land.

EXISTING PROTECTION CASE

The areas that are currently protected in Argentina are the harbors. Since we did not have the information to calculate the costs of upgrading these harbors with accelerated sea level rise, we used the value documented by the IPCC (1990). For the 1-meter scenario, this cost is $262 million.

PROTECTION OF IMPORTANT AREAS

The cost of protecting the areas of medium to high development are broken down into nourishment of tourist beaches, construction of sea walls for towns and cities, and the upgrading of harbors (Table 9). The largest constituent of the cost of protection for this option is beach nourishment, which represents 45–75 percent of the total cost of protection for the 1-meter scenario.

TABLE 9. COSTS OF PROTECTION OF IMPORTANT AREAS (MILLIONS OF 1991 U.S. DOLLARS) AND PERCENT OF GROSS INVESTMENT (1987) OVER 50 YEARS (2051–2100)

Response	**Sea Level Rise (m)**		
	0.5	*1.0*	*2.0*
Important Areas			
Nourishment	$175-718	$267-982	$453-1,514
Sea walls	31-33	51-54	109-112
Upgrading harbors	131	262	524
Total	**337-883**	**580-1,298**	**1,086-2,150**
% Gross investment	0.1-0.3	0.2-0.4	0.3-0.7
Total Protection			
Added sea wall costs	268-1,043	632-1,413	1,830-2,549
Total	**605-1,925**	**1,212-2,711**	**2,916-4,699**
% Gross investment	0.2-0.6	0.4-0.9	0.9-1.5

TOTAL PROTECTION CASE

This option includes the protection of the entire coastline of Buenos Aires Province, along with the areas that would be protected in the important areas protected case. The construction of sea walls becomes the largest constituent in this case (Table 9). This is because the length of coastline that would be protected is very large—approximately 1,300 km. This option would cost twice as much as the protection of important areas case, yet would only decrease the economic value lost by 1 percent.

APPROPRIATE RESPONSES

PROTECTION OF IMPORTANT AREAS

The protection of important areas case appears to be the most realistic option in the event of sea level rise. In this case, the major cost of sea level rise in Argentina would be nourishing tourist beaches. Tourism is important in Argentina, even though it is mainly a domestic industry. The protection of harbors would also be costly. The harbors must be maintained, as they are crucial for movement of goods into and out of the country, including the export of farm products, fish, oil and natural gas, and several types of manufactured goods.

Sea level rise may also damage fisheries due to the loss of wetlands. Of the 105,000 tons of fish exported in 1988, 21,000 tons were fish that are dependent on estuaries in one stage of their life cycle. This represents $13 million (or 12 percent) of a total $104 million received in revenue from fish exports (Fundación Atlántica, 1989). These numbers, however, do not show the total impact of the loss of wetlands, since many local fisheries along the La Plata River coastline also depend on estuarine fish for subsistence.

The major impact of accelerated sea level rise on the city of Buenos Aires will be the necessity to upgrade the harbor facilities and the potential inundation and erosion of the coastal areas that are not protected by harbors or sea walls in Buenos Aires and its suburbs.

Protecting against sea level rise would be a major cost for Argentina. At present, despite Argentina's relatively large GNP, it would be very difficult for the government to implement a major coastal protection program because the country's current efforts to rebuild its economy place a higher priority on other issues. In addition, government-backed activities are presently being reduced to a minimum level. On the other hand, an increasing awareness of environmental problems may induce some support for coastal planning and protection, though not at a full level of commitment.

COASTAL ZONE MANAGEMENT PLANS

The best method for dealing with the potential problems of sea level rise is within the framework of a comprehensive coastal zone management plan that addresses all coastal problems. The cost of protecting the major developed areas of the coastline against a 1-meter rise in sea level ranges between $580 and $1,298 million. This represents 0.2 to 0.4 percent of Argentina's 1987 gross investment over 50 years (2051–2100).

FOLLOW-UP STUDIES

The following "case" studies would be useful:

1. A vulnerability assessment of the Parana River delta, including an analysis of the historical pattern of flooding, of the defense works completed or planned, and of general development programs.

2. Modeling of the hydrologic response to sea level rise in the area of the Samborombon Bay wetlands and associated environments. Estimations of land loss and socioeconomic impacts.

3. A survey of the coastline south of Rawson (Chubut) down to Tierra del Fuego, including evaluation of the socioeconomic impacts.

4. A detailed assessment of the development adjacent to the Bahía Blanca estuary, including a number of harbor and industrial activities.

The completion of these studies, including the already-existing data base and projects under way by various organizations within the country, will help in developing a national coastal zone management plan.

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ASSESSMENT OF THE VULNERABILITY OF GEOGRAPHE BAY, AUSTRALIA, TO SEA LEVEL RISE

Robert C. Kay
Coastal Risk Management
Norwich, United Kingdom

Ian G. Eliot
State Gov. of Western Australia
Department of Planning and
Urban Development
Perth, Australia

Geoff Klem
State Gov. of Western Australia
Department of Planning and
Urban Development
Bunbury, Australia

ABSTRACT

The mainland Australian case study focuses on 87 km of coast in Geographe Bay, in the southwest of the state of Western Australia. This coastline is one of Australia's most vulnerable to present environmental variability. It is therefore, vulnerable to the future potential impacts of sea level rise and climate change.

The case study took three months, with most of the work undertaken by a consultant contracted for 50 percent of his time. It was based on existing work, although some limited new research was carried out on potential physical impacts. In addition, a one-day workshop was convened to discuss the interim results of the study and analyze the applicability of the IPCC Common Methodology for formulating a response strategy in Western Australia. The 15 workshop participants were drawn from federal, state, and local governments, universities, and research organizations.

The approximate cost of the study was AUS $50,000, including consultancy fees, estimates of time spent on the project by the consultant and workshop participants, as well as costs for materials.

The case study was valuable in that it highlighted the mechanisms for assessing the impacts of sea level rise, indicated where information was unavailable, and identified the processes for implementing response strategies within the state. The Common Methodology is a useful basis for assessing impacts on a regional scale. However, it does not allow for a meaningful evaluation of potential response strategies. A complementary planning-based methodology for formulating response strategies, combined with principles of risk management, is deemed necessary for this to be achieved in Western Australia. A similar planning-based strategy would have applicability for other Australian states.

THE STUDY AREA: GEOGRAPHE BAY

Australia's mainland coastline is approximately 30,000 km long (Table 1), with about 75 percent made up of beach/dune, salt marsh/mangrove, and estuary/delta systems. It is this proportion that could be considered physically vulnerable to the potential effects of sea level rise.

TABLE 1. NATURAL SYSTEM DATA: PHYSICAL CHARACTERISTICS

Type of data	Units	Study area	State (1)	National (1)
Natural coast types				
beach/dune	km		4766	15,934
salt marsh/mangrove	km		1985	6,511
cliff soft	km			
cliff hard	km		2535	5,852
- granite		3.5		
- basalt	km	1.5		
hard rock cliffs + bay beaches	km			
- granite		11.0		
- limestone		2.0	472	986
shore attached barrier/spit	km			
- low profile		38.5		
- high profile		30.5		
shore detached barrier/spit	km			
estuarine/delta	km		429 (2)	910 (2)
other			13	84
Totals		87.0	10,200	30,277
Artificial coast type	km	(3)		
sea walls (+/- groynes)	km	1.0		
river walls/embankments	km	0.0		
groynes (without seawall)	km	4.0		
breakwaters	km	0.0		
Regional subsidence (total)	mm/yr	0.31 (4)		
natural subsidence component	mm/yr	0.31 (5)		
human induced subsidence component	mm/yr	0.00 (5)		
Design water level (open ocean)	m	2.4 (3)		
design criteria (return period)	m	n/a		
datum level		A.H.D. (3a)		
Mean tidal range	m	0.5 (6)		
tidal type		Diurnal/mixed		
Seasonal mean sea-level fluctuation	m	0.2 (6)		
Annual average wave height	m	0.5-0.9 (7)		
mean annual maxima	m	3.0-4.0		
design waveheight	m	3.5-5.0 (7a)		
Annual average sediment loads	tonnes/yr	n/a		
Annual average river dischange	m3/s			
Design discharge	m3/s			
Area with (potential) salinity poblems	km2			

1 Data from Galloway et al (1984).
2 Galloway's "water" classification can be approximated to estuaries.
3 Data from West Australian Department of Marine and Harbours (DMH)
Timber groynes designed to be overtopped
3a Australian Height Datum (mean sea-level)
4 Source Wallace, D. (1989) Australian sea-level trends.
5 Subsidence assumed to be 100% natural in this study. No evidence to suggest otherwise
6 Source Australia National Tide Tables 1992, Austalian Government Publishing Service.
7 DMH waverider bouy data and inferred waverider data (wave energies around the Bay)
7a Deep water design waveheight (around the bay)

Geographe Bay is a north-facing, open-ocean coastline about 200 km south of Perth, the capital of Western Australia. The study area covers 87 km of coastline within the state of Western Australia (Figures 1 and 2). This is a small fraction of the total length of Australian mainland coast. However, the sheltered open-ocean environment has attributes, and experiences management problems that are found in surge-dominated environments throughout Australia, particularly southern Australia. Similar environments are found throughout the world and are characteristic of tropical and subtropical coastlines protected by islands and offshore reefs, including coral and limestone reefs.

There are three main types of coast within Geographe Bay (Figure 2). To the west is Cape Naturaliste, a hard-rock granite promontory that forms part of the Leeuwin-Naturaliste Block. In the central/southern section is a low, sandy, barrier system, less than 4 meters above mean sea level, approximately 500 meters wide, and backed by a broad estuarine system of high significance to migratory wading birds (Table 2). An extensive and high dune-barrier complex makes up the northeastern section of the study site. The northern reach of the study site is comprised of 1 km of sandy beaches, alternating with low-amplitude, rocky headlands. The northern boundary of the case study area is controlled by a basalt sill.

TABLE 2. NATURAL SYSTEM DATA: HABITATS AND SPECIES

Type of data	Units	Study area (1)
Dunes		
area	km2	
biodiversity	species/km2	
red data book species	species no	
Wetlands		
area	km2	1500 (2)
biodiversity	species/km2	10 (3)
red data book species	species no	0 (4)
Sea-grass		
area	km2	
biodiversity	species/km2	
red data book species	species no	0
Total "ecological" area	km2	865 (5)
Total "special" ecological area	km2	720 (6)

(1) West Australian Department of Conservation data and Land Management data
(2) Total area of the Vasse Wonnerup estuarine system only
(3) Estimated from 78 waterbird species within 7.2km2 of RAMSAR area (Note 5)
(4) 2 bird species on national important species list; none in Red Book
(5) State Nature Reserve (includes "special ecological area" - note 6)
(6) Proposed RAMSAR designation for Vasse-Wonnerup estuary
(includes 68ha of State Reserve "ecological area" - note 5)

Geographe Bay was chosen for the case study because of its physical vulnerability to present climate extremes, future climate change, and sea level rise. The coastal zone is also subject to extreme development pressures. The combination of these factors has generated a suite of planning and engineering responses to existing vulnerability issues. Albeit in microcosm, the area already shows many of the future planning and impact mitigation problems that other sections of the Australian coastline may face due to sea level rise.

FIGURE 1. LOCATION DIAGRAM

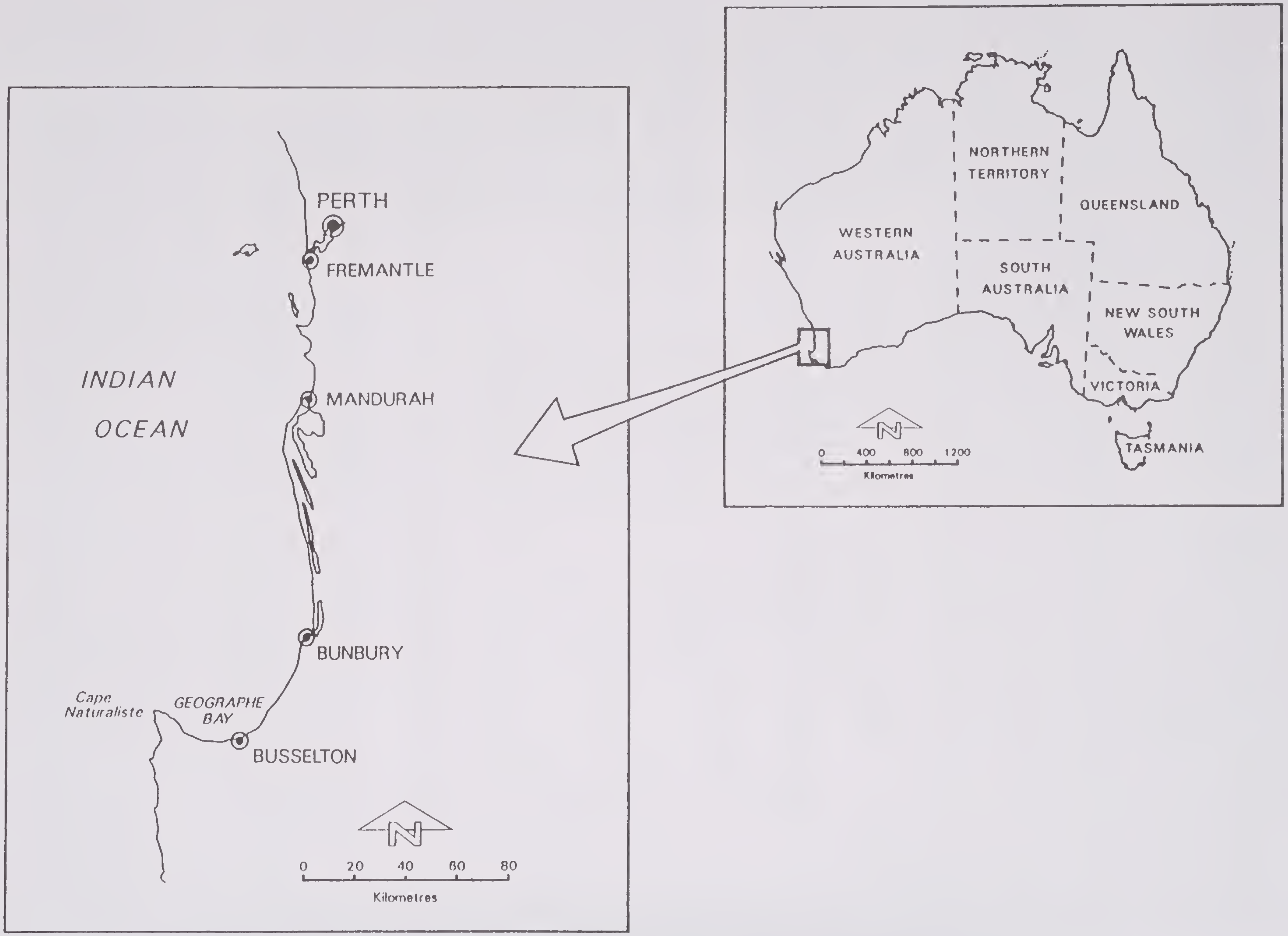
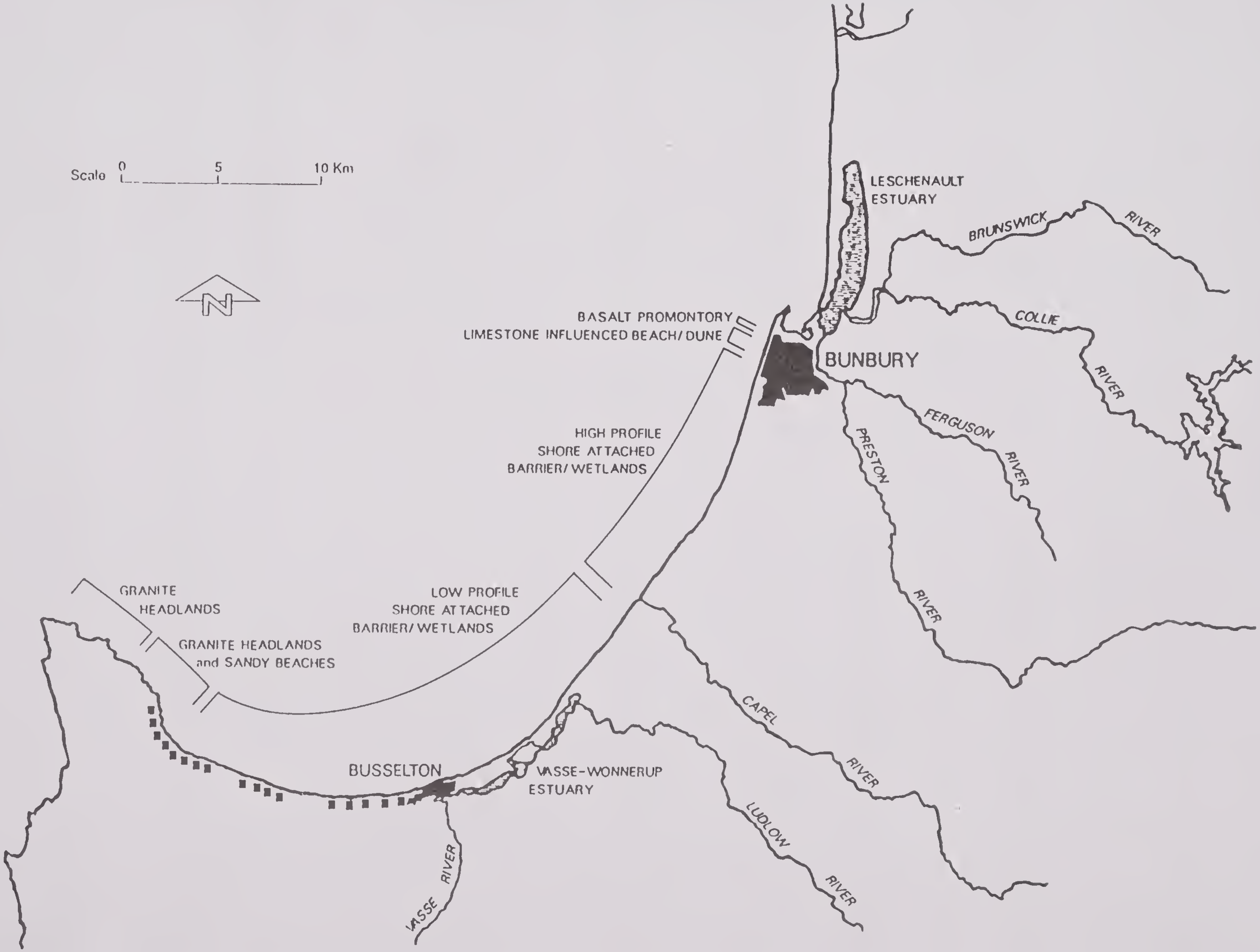


FIGURE 2. COASTAL GEOMORPHOLOGY



COASTAL MANAGEMENT IN AUSTRALIA

Coastal management problems, including those that have to be considered as potential responses to accelerated sea level rise, occur within a sociopolitical framework. Although the case study was conducted for a small part of the Australian mainland, developing a response strategy requires interaction between several levels of government and the local communities. This is typical of all Australian states, where responsibility for day-to-day management of the coast is vested in local government authorities who act according to the advice from state government agencies and community organizations.

This study is not a complete analysis of the impacts of sea level rise. While readily available data were included, there is a notable lack of data available for several categories of information. This may indicate that the Common Methodology does not focus on a level of detail that is appropriate for decision making in Western Australia. The degree to which it is a methodology common to all nations is a matter that requires further consideration.

COASTAL MANAGEMENT IN AUSTRALIA

The coast plays a central role in the culture of most Australians. Approximately 83 percent of Australia's population, or 10.5 million people, live within coastal municipalities, compared with 49 percent for the United States (Cullen, 1986). An estimated 26 percent of the nation's population live within 3 km of the shore. The distribution of this population is highly uneven, being clustered around the coastal cities and in small coastal towns. There are long stretches of very sparsely populated coast, especially in the northwestern part of the country, and the center of Australia is very sparsely populated. Hence, national population densities are low by global standards.

The Australian government recognizes the importance of the coast to the public. Nearly every year since 1970, the Australian government has initiated a review of some aspect of coastal management policy and practice. The most recent inquiry completed was an examination of the House of Representatives (HOR) Standing Committee on Government, Recreation, and the Arts of the protection of the coastal environment (HOR, 1991). The inquiry pointed to the need for a more coordinated approach to coastal management by all tiers of government.

This inquiry has been followed immediately by the initiation of a Resource Assessment Commission inquiry into management of coastal resources, particularly those in the developed areas (RAC, 1991). It is anticipated that the commission's inquiry will lead to a more coordinated approach to coastal management, and possibly to the establishment of a national coastal management policy. However, at present there is no mechanism that ensures a coordinated approach between the federal and state agencies, encourages interstate discussion on coastal management, or requires community involvement in the federal government's decision-making process.

In the absence of clearly enunciated federal coastal management policies, the responsibility for determining coastal management policy falls to state and local governments, where there is an established mechanism for liaison and community involvement. State and local government policies are implemented through structured programs. The state governments are responsible for environmental assessment. This includes assessing the potential impacts of sea level rise, and identifying and implementing strategies for alleviating those impacts. The ability to implement strategies will ultimately depend on resource provision, the establishment of funding programs, and coordination of research and monitoring priorities. At this stage, it is not clear which level of government in Australia will provide the necessary resources, and which agency coordinates what aspects of coastal management at the federal level.

COASTAL MANAGEMENT IN WESTERN AUSTRALIA

In Western Australia, coastal management is directed by plans that guide the use of coastal land for conservation, recreation, and development. Preparation of the plans has required cooperation among approximately 10 state government departments with particular interests in coastal management, as well as representatives of local government. Each tier of government has a formal responsibility to consult with the local community in the preparation of coastal plans. Historically, the plans have been prepared as nonstatutory, advisory documents in Western Australia. More recently, components of the plans—i.e., policy matters—have been incorporated in District Town Planning Schemes, where they have a stronger statutory base, which enables policy implementation.

The process of decision making required for preparing plans is fundamental to the development of any mechanism for assessing and preparing strategies for mitigating the potential impacts of sea level rise. Hence, it is important to consider in more detail the coordinating mechanisms that support coastal management in Western Australia. Figure 3 illustrates the coordinating structure used in Western Australia. While Western Australia may not be considered typical of all Australian states in its coastal management structure (Queensland Government, 1991), there is a need for the IPCC impact assessment procedure to be incorporated within state coastal decision-making processes as soon as possible if it is to be effective. This can be demonstrated by considering how coastal management plans are designed and implemented.

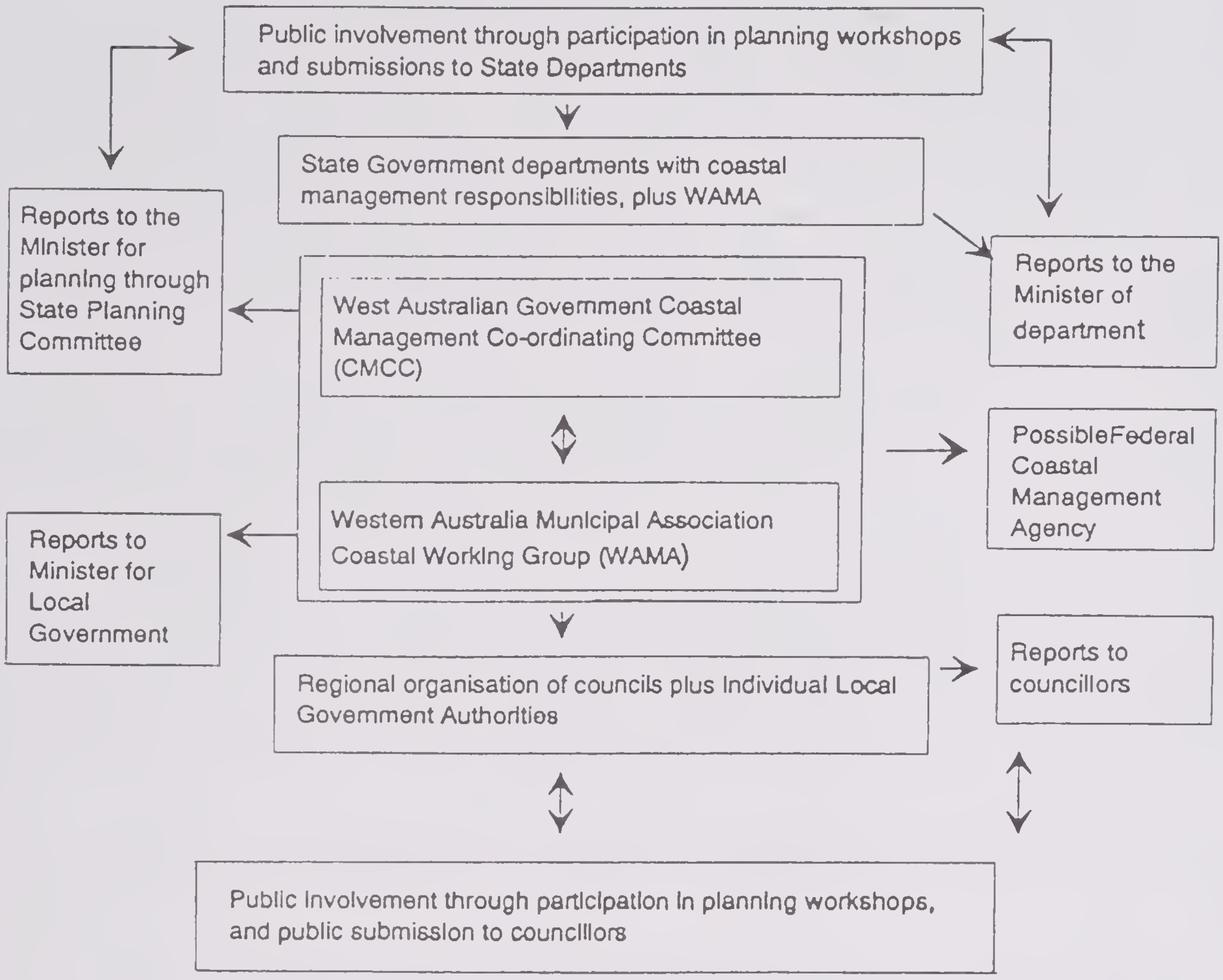
A coastal management plan is usually initiated by a local government authority that approaches one of the state government agencies responsible for some aspect of coastal management. For example, the request from local government may be for construction of a marina, a strategy for land allocation, or a program for managing access roads to the beach. The plan is then prepared on a cooperative basis between the relevant state and local government agencies. Its preparation also requires a public involvement program that includes community workshops at the plan formulation phase, public presentation of the draft plan, and formal public submissions on matters raised in the plan when it is released. The plan is then implemented by the local government authority as part of its works program. However, if the community does not perceive the issue to be a threat, and if local government does not accept responsibility on behalf of the community, then it is unlikely that international and national initiatives will be taken.

ANALYTICAL METHOD

The Common Methodology was followed as closely as was feasible, given time constraints, the availability of data, and constraints inherent within the methodology itself. The tables within the Common Methodology were adapted to suit local conditions, and are numbered here as Tables 1–9.

Rather than attempting to collect detailed data for the entire study area, results were compiled for five, 1-km-wide sections of coast (Figure 4), selected because they represent a wide range of physical and cultural issues. The total suite of problems occurring in these sectors characterizes issues found in the wider region.

FIGURE 3. WEST AUSTRALIAN COASTAL MANAGEMENT DECISION-MAKING NETWORK

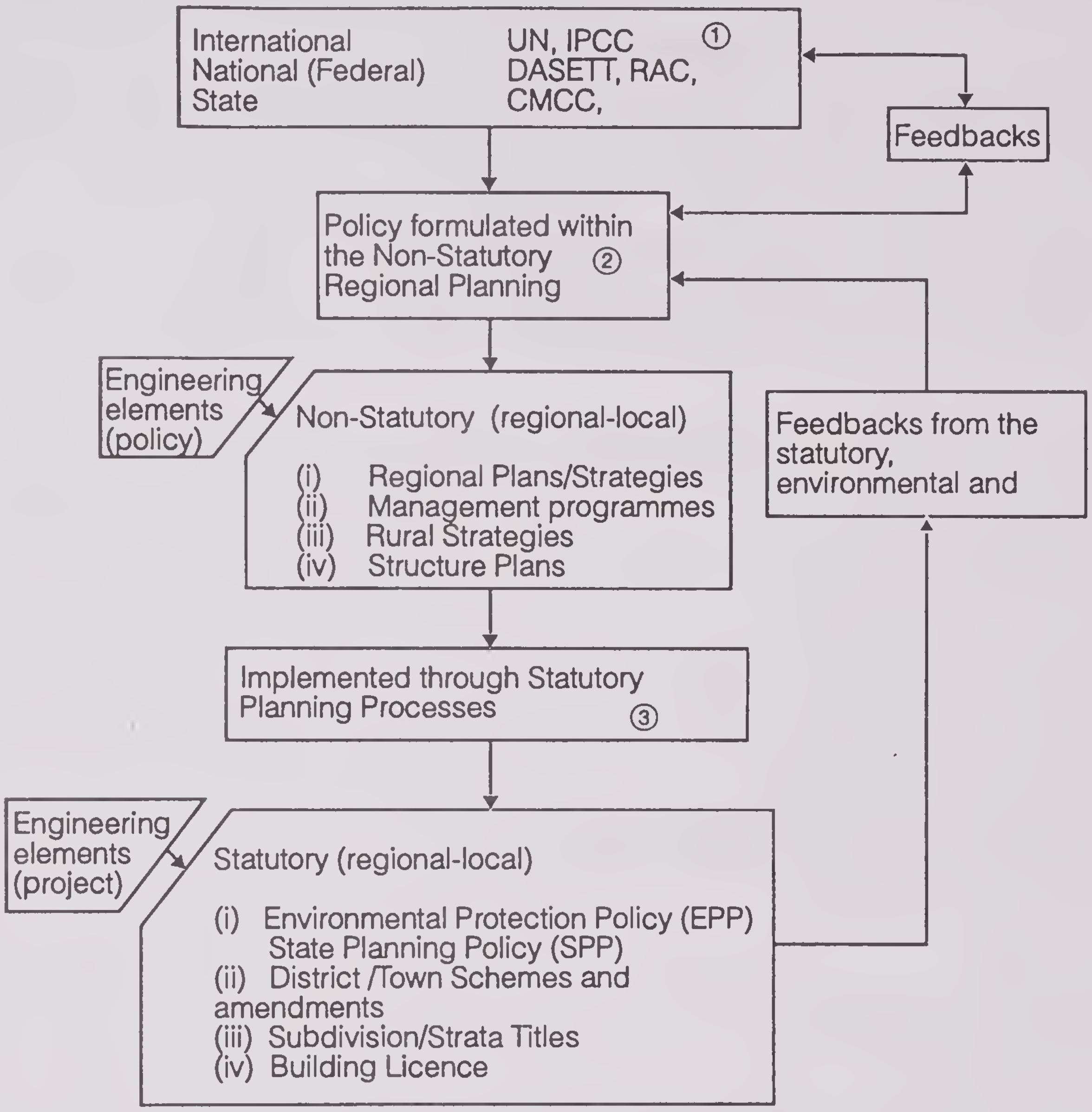

Public involvement through participation in planning workshops and submissions to State Departments
State Government departments with coastal management responsibilities, plus WAMA
Reports to the Minister for planning through State Planning Committee
Reports to the Minister of department
West Australian Government Coastal Management Co-ordinating Committee (CMCC)
Western Australia Municipal Association Coastal Working Group (WAMA)
PossibleFederal Coastal Management Agency
Reports to Minister for Local Government
Regional organisation of councils plus Individual Local Government Authorities
Reports to councillors
Public Involvement through participation in planning workshops, and public submission to councillors

The Common Methodology establishes boundary conditions within its first table. This table was expanded and restructured for the project by the Commonwealth Scientific and Research Organization's Division of Atmospheric Research (Table 3). This was necessary in order to indicate the parameters that were considered to be appropriate to the study.

The Common Methodology was also extended to include factors important to formulating a response strategy for Western Australia: (1) the recreational value of the coastal zone, (2) its heritage issues, and (3) its regional economic and demographic settings.

In addition, an outline schedule and budget for conducting a full assessment of the impacts of sea level rise is given in Table 4. It includes components that are deemed necessary for assessing the impacts on Geographe Bay, including those listed above. The components in Table 4 could be used as a basis for an assessment methodology that may be applicable to other Australian coastal environments.

FIGURE 4. INCORPORATION OF SEA LEVEL RISE STRATEGIES IN THE WEST AUSTRALIAN PLANNING PROCESS


International
National (Federal)
State
UN, IPCC ①
DASETT, RAC,
CMCC,
Feedbacks
Policy formulated within the Non-Statutory Regional Planning ②
Engineering elements (policy)
Non-Statutory (regional-local)
(i) Regional Plans/Strategies
(ii) Management programmes
(iii) Rural Strategies
(iv) Structure Plans
Feedbacks from the statutory, environmental and
Implemented through Statutory Planning Processes ③
Engineering elements (project)
Statutory (regional-local)
(i) Environmental Protection Policy (EPP) State Planning Policy (SPP)
(ii) District /Town Schemes and amendments
(iii) Subdivision/Strata Titles
(iv) Building Licence

Most commonly used implementation tools in State and Local Government planning.
(i) District /Town schemes and amendments
(ii) Subdivision/Strata Titles
(iii) Building Licence

1. Abbreviations in alphabetical order

EPA	Environmental Protection Authority (State)
DASETT	Department of the Arts, Environment, Tourism, and Territories (Federal)
DPUD	Department of Planning and Urban Development (State)
IPCC	Intergovernmental Panel on Climate Change
OCM	Office of Catchment Management (State)
RAC	Resource Assessment Commission (Federal)
UN	United Nations

2. The Perth Metropolitan Region is the only part of Western Australia that has a statutory region plan.

TABLE 3. RESTRUCTURED TABLE OF BOUNDARY CONDITIONS FOR COASTAL IMPACT ASSESSMENTS

Sea-level rise boundary conditions

Boundary conditions	Units	ASLR1	Mid-ASLR	ASLR2
Accelerated sea-level rise				
Total sea-level rise by 2100	m	0.3	0.66	1.0
Total sea-level rise by 2030	m	0.1	0.2	0.3
Other conditions: For each sea-level rise scenario there needs to be three scenarios for changes in meteorlogical and other factors leading to extrems events and other conditions affecting coastal regions, as in Table 3b, below.				

Boundary conditions of meterorological and other factors

Variable	units	Decrease	"No change"	Increase
Change in storms				
Hurricanes				
Number change	%			
Central pressure	HPa			
Intense extra tropical lows				
Number change	%			
Central pressure	HPa			
Changes in wave climate				
Modal annual wave height change	m			
Change in annuual wave energy	w/m2			
Modal wave direction	Deg			
Change in temperature				
Summer	°C			
Winter	°C			
Change in precipitation				
Summer total	%			
Winter Total	%			
Change in frequency of 10 yr event	%			
Change in frequency of 50 yr event	%			
Change in evaporation	%/°C warming			
Summer	%/°C warming			
Winter	%/°C warming			
Change in 10 yr peak river discharge				
summer	% change			
winter	% change			
Sediment loading	t/yr			

Produced with assistance from the Commonwealth Scientific and Research Organization (CSIRO) Division of Atmospheric Research.

TABLE 4. ESTIMATED TIME AND COST FOR ASSESSING RESPONSE STRATEGIES FOR GEOGRAPHE BAY

Research area	Example Description	Estimated time (months)	Estimated cost (1000s
Core biophysical coastal research			
Physical dynamics of the bay	Bay shape, megacusps	36	750
Biological dynamics of the bay	Seagrass effect	24	100
Other physical research			
Storm surge return frequencies	Cyclones/extra-tropical lows	6	30
Freshwater flood hazard			
Coastal evolution prediction			
Historical data analysis		24	120
Coastal evolution modelling	Sediment budgets	24	240
Economic impact assessment			
"Normal" economic evaluation	Land values etc.	6	20
"Environmental" economic valuation	Hedonic, recreational pricing	24	100
Response strategy evaluation			
Analysis of leglislative and descision making			
Feasability or risk sharing and risk transfer	Land titles, liability issues	12	100
Engineering response feasability			
Comunity awareness and education programmes	Local meetings	6	50
Commnity involvement programmes	Information preparation	24	25
Analysis of potential community biases	and distribution	12	100

Estimated totals	36 (1)	$1,635

Assumes concurrent timing as part of an integrated research, assessment, and implementation program.

RESULTS

BIOPHYSICAL IMPACTS

EROSION

Traditional models of predicting future shoreline change break down when applied to Geographe Bay. Instead, a composite shoreline evolution model must be built that includes the following interacting variables (key references are bracketed):

1. Changes in the shape (coastal plan form) of the bay (Hsu and Evans, 1989; Hsu et al., 1989).
2. Sea grass influence on shoreline dynamics (Searle and Paul, 1976; Walker et al., 1988).
3. Historic variability of the shoreline (WADPUD, 1992; WADMH, 1984).
4. Sediment budget constraints (Everts, 1987; Reidel and Byrne, 1988).
5. Shoreline planform considerations (Bruun, 1962 and 1988).

Note that these factors are not intended as a mutually exclusive list.

Such a composite model has *not* been constructed for this study, although it is seen as a priority for future vulnerability assessment work. Shoreline evolution modeling of this type would be applicable to other sections of the world's coast whose shape is dominated by refracted swell waves (e.g., bay sections of Australia's east, south, and west coasts, and the west coasts of North and South America and South Africa). In these areas, there are crucial implications of a changing plan form due to accelerated sea level rise (Hsu et al., 1989).

Changes in coastal plan form would mean a general deepening of the bay's shape, resulting in the erosion of the southern section of Geographe Bay and accretion in its northeastern section. In other words, future erosion due to sea level rise will be highly nonlinear around the bay.

This nonlinearity in predicting changes in the shape of the bay is compounded by the important role that sea grass plays in defining the location of erosion and depositional "nodes" along the southern section of the bay (Paul and Searle, 1978). Specifically, erosional blowouts in the sea grass meadows focus wave energy on sections (nodes) of the coastline, enhancing the erosion there. Temporal and spatial changes to the morphology of these nodes are poorly understood, but they can be expected to continue in the future, with or without sea level rise and climate change.

Faced with the above problems in assessing future shoreline change, the Department of Planning and Urban Development used "essentially qualitative (erosion) estimates based on a 'rule-of-thumb' approach established by experience in the region" (WADPUD, 1992). Such estimates were used in combination with amenity and recreational considerations by the Department to establish appropriate criteria for establishing setback requirements for shoreline development. The Department recommended that in the southern section of the bay:

> Any sea level rise will cause a dramatic retreat of the shoreline as the contemporary dunes contain only a low volume of sand for redistribution. Such a retreat could reasonably be expected to be on the order of 1:100; that is, a 1-meter rise in sea level could lead to a 100-meter retreat of shoreline. However, such estimates should be verified for the local area as a basis for future planning and management.

Therefore, in the absence of more sophisticated data, the planning authorities have used a simple Bruun "rule" with a 1:100 (Bruun, 1962) constant to predict erosion. This is consistent with an analysis of the variations in mean sea level and beach for Scarborough Beach in Perth, 200 km north of the study area (Clarke and Eliot, 1983). By accepting this ratio, the emphasis is then placed on the developers of coastal land to undertake more detailed studies of coastal evolution as new development is proposed close to shore. One problem with this is that there is no long-term commitment to the monitoring of shoreline movement and coastal processes within the region.

These arguments have meant that *no* coastline evolution predictions have been made for this study. This is because the "rule-of-thumb" approach of shoreline evolution by 2030 using a 1:100 Bruun factor with the "Business-as-Usual" scenario for sea level rise (Table 2) may not cause significant property damage around the bay. There are sufficiently wide development setbacks already in place, which stem from the tradition of establishing coastal crown "reserves" in Western Australia (O'Brien, 1988). However, the form of the coastal sand barrier suggests that application of the Bruun rule may not be wholly appropriate; hence, an "approximation" approach was warranted.

An attempt to produce more sophisticated projections of shoreline changes was not attempted because of fundamental uncertainties in the response of the bay as a whole to sea level rise and climate change. An ad hoc approach to shoreline response modeling would have understated the complexity of this physical response.

If there proves to be a small amount of projected property damage in the immediate future, as the "rule-of-thumb" approach predicts, then this presents two major problems in any vulnerability assessment. First, development not vulnerable during the next 40-50 years may become vulnerable after this time—perhaps more so because there is no buffer zone left between it and the sea as a result of the coastal setback zone being eroded away. Second, loss of the existing coastal buffer zone through erosion will affect on the local economy by reducing the appeal of this part of the coastal zone to tourists and people retiring to the area. This is likely because the sea level rise will displace key recreational areas along the coast. This is not specifically addressed in the Common Methodology.

FLOODING

Flood hazards in the southern section of the bay are posed by both cyclones and rainstorms. The 1 percent annual ("1 in 100") flood hazard area in and around the Busselton area has been delineated by the West Australian Water Authority (WAWA, 1987). The 1 percent annual flood height is 1.1 meters above mean sea level. These flood hazard maps were drawn to guide local planning authorities on the safe location of new development. However, the WAWA study covers only half of the bay's southern section, where urban development either exists or is possible in the future. Determination of the flood hazards in the agricultural land west of Busselton is of low priority to WAWA and is not planned for study. This is a problem for assessing the impacts on the entire hazardous area. The area is increasingly becoming subject to development pressures and supports a subdivision that includes expensive holiday homes. The land value of the oceanfront homes alone is AUS $300,000 per 100 meters of coast (Table 5).

TABLE 5. CRUDE LAND PRICE VERSUS DEFENSE COST CALCULATION

Data compliled from Tables 7 and 9

Type of data	Value AUS$	Blocks per 100m of coast	$ per 100m of coast
Assume the 1st, 2nd, and 3rd line blocks are potentially vuln (1)			
1st line block value (2)	100,000	3	300,000
2nd line block value	70,000	3	210,000
3rd line block value	60,000	3	180,000
Defence cost using filled timber groynes per 100m of coast (3)			17,000 (4)
Approximate hedonic premium attached to coastal environment? (5)	40,000	3	120,000

(1) These figures are chosen to illustrate potential vulnerability only. A detailed assessmentof exact number of blocks has not been undertaken.
(2) Land value only (see Table 7).
(3) Data from Table 9.
(4) The positive cost-benefit ratio this table infers does not lead straight into a Protect Option (see text).
(5) A full hedonic pricing study needs to be undertaken to assess the relevance of these figures. Assumed to be the price difference between $100,000 and $60,000 for the "present condition of the coastal zone". Data of this form could be used to produce surrogate values of the value of the coastal environment.

In contrast to flood hazards from rainwater, there has been no detailed study of flood hazards from cyclones in Geographe Bay. The most recent major tropical cyclone was Cyclone Alby in 1978, which generated a surge 1.25 meters high and coincided with a 1.2-meter high tide, yielding a total water level some 2.45 meters above the mean water level. Busselton is a maximum of 3 meters above mean sea level, with the average height being 2–2.5 meters (WAWA, 1987). The surge thus sent flood waters down the main street of Busselton, causing widespread damage.

As part of this study, the Australian Bureau of Meteorology's cyclone-surge model was run to analyze the sensitivity of the bay to perturbations from tropical cyclones. The results in Table 6 show that the entire barrier system in the southern section of the bay is vulnerable to cyclone flooding. However, it must be stressed that the return frequency of the surges depicted in Table 6 has not yet been determined. Hence, the data must be treated with extreme caution.

TABLE 6. CYCLONE SURGE SENSITIVITY ANALYSIS FOR SOUTHERN GEOGRAPHE BAY (1,2)

Modelled meteorology	Track	Modelled central pressure range (hPa)	Modelled max. surge height (m)	Modelled surge and tide (m) (4)
Cyclone Alby	West of mainland	960-970	0.7 (3)	1.9 (5)
Cyclone Alby - modified "worst case"	Through Cape Naturaliate	960-970	2.6	3.8
Cyclone Alby - modified "worst case" track and "Worst case" central pressure	Through Cape Naturaliate	950	3.2	4.4

(1) Data supplied by the West Australian Bureau of Meteorology
(2) The figures in this table do not have associated return frequency statistics
(3) Recorded maximum surge height 1.25m at Busselton 4/4/78
(4) Assumes the same tidal conditions as during recorded surge (1.2m above mean water high tide)
(5) Recorded surge and tide 2.45m above mean-sea-level

It is also important to note the differences in impacts on the southern section of the bay between tropical cyclones and extratropical lows. Any study of the return frequency of storm surges will have to address both types of storm systems and their potential shoreline impacts. Tropical cyclones are of short duration and high intensity. They produce rapid increases in water level that last 3 to 12 hours. There can be significant wave activity on the surge waters, but usually a fully developed sea does not occur. Thus, the physical impacts on the coast are flooding and the transport of sediment from the beach landward across the barrier into the back-barrier wetland system.

In contrast to the tropical cyclones, extratropical (winter) lows do not produce spectacular storm surges, but have higher-energy and more persistent waves. They last long, usually 2 to 3 days, and are moderately intensive. Flooding generally doesn't occur, but sediment is combed down from the subaerial beach and transported offshore. This is manifested as shoreline erosion.

SOCIOECONOMIC IMPACTS

Western Australia does not use economic analysis techniques as a basis for coastal management decisions. However, there is an awareness in the state that such techniques will be useful in the assessing the impacts of potential sea level rise.

REGIONAL ECONOMY

The tourism income and house price structure in Busselton provide surrogate measures of the value of the Geographe Bay coast in its present condition. Using environmental economic techniques to attempt quantification of such values is seen as an important addition to the Common Methodology. However, these data do not attempt to attribute dollar figures to the value "of" the environment (its "intrinsic value"), but rather the value "in" the environment (Pearce, 1991).

This also raises the issue of "opportunity costs," the benefits foregone in other policy areas by deploying resources for building structures to withstand sea level rise (Synnott, 1992). The opportunity cost concept is a subtly different measure of a nation's "capacity to cope" with the potential impacts of sea level rise, measured in terms of its gross domestic product—different because political expediency and public concern can be included in the economic assessment process.

The land-value data collected for the case study show the economic premium placed on an oceanfront location. This hedonic price method (Garrod and Willis, 1992) would lead to a first estimate of the implicit value of the coast, as viewed by land purchasers if it were extended to a detailed study of regional residential land values. Other environmental variables that influence land values in the area would have to be compensated for in such a study.

The initial data show that the real estate market attaches a premium to land immediately adjacent to the coast. The gradient of land price reduction away from the coast is steep (Table 7). Thus, it can be assumed that the present environmental condition of the coast is valuable in dollar terms. This may mean that any degradation in the coastal environment will be reflected in the absolute differences, and gradient, of land-value differences away from the coast. Such coastal environmental degradation may result from accelerated sea level rise, or from a response strategy designed to protect the property assets at risk.

This simple attempt at hedonic pricing would have to be carried out in conjunction with an analysis of the value of structures in defended and/or already degraded parts of the bay. The "defense premium" in the land price could then be obtained.

DEMOGRAPHICS

Researchers of natural hazards stress the importance of analyzing the demographic structure of a community in order to evaluate its response to hazard (Ericksen, 1986). Differences in the demographic profiles of communities—such as age and sex—and their previous experiences of hazard can have important influences on the impact of natural hazards, both in pure economic terms and through lives saved.

Busselton is one of the most rapidly expanding areas in the state. Its population of 13,500 is growing by approximately 3 percent a year (Table 8) (WADPUD, 1988). However, this expansion is not uniform across all age ranges. There has been a significant increase in the population above

65 years old and a doubling of it in absolute numbers. At the same time, significant reductions have occurred in the under-14 population (ABS, 1990). Because Busselton is developing as a retirement area, much of the population will not have experienced a major storm on the coast. The past 40 years have shown a steady decline in the storminess of southwestern Western Australia. One outcome of this is that local citizens will base their judgment of a greenhouse-induced climate change on a benign period of climate and a quiescent phase of shoreline change.

TABLE 7. SOCIOECONOMIC SYSTEM DATA: USES AND VALUES

Type of data	Units	Quindalup	Broadwater	Busselton	Minninup	Bunbury
Land use - capital value	1000s AUS$ (1)					
Residential - Coastal frontage	· per	100	100	120		
- 2nd line back from coast	redidential	60-80	60-70	60		
- 3rd line back from coast	block	60-70	60	60		
Agricultural	AUS$/1000m2 (2)	0.25-0.4	0.25-0.4	0.25-0.4	0.1-0.2	n/a (3)
Commercial	AUS$/m2			225-250		
Land use - production value						
- Tourism revenue	AUS$/yr					
- Agricultural revenue (wetlands)	AUS$/yr/Ha	70-100 (4)	70-100	70-100		
- Agricultural revenue (drylands)	AUS$/yr/Ha					
Coastal fisheries - production value	AUS$/yr					

(1) Unimproved land values only. ie. no property component. Data from WA Valuer Generals' Office.
(2) Values converted to $/residential block area for comparison purposes
(3) Potential impact area a road/car park area
(4) Figures from WA Department of Agriculture

Therefore, the aging population is at more risk from the potential impacts of sea level rise and climate change than the younger residents of other coastal areas. This may be a problem faced in other coastal areas of the developed world, and may need to be included in an expanded Common Methodology.

HERITAGE

There are effectively two separate heritage issues in Western Australia: aboriginal heritage and European settlement heritage. Heritage issues are introduced in this assessment because of their dual importance in formulating response strategies.

First, the Common Methodology needs to be expanded to account for the value of heritage assets. The coast of Geographe Bay has very important aboriginal and European heritage sites. The "Wardanindi" tribe was part of an aboriginal population of about 6,000 in the region before European settlement in the mid-1800's (Tindale, 1974), and there are numerous sacred and other sites of importance as a result.

TABLE 8. SOCIOECONOMIC SYSTEM DATA: GENERAL INFORMATION

Type of data	Units	Study area	State	Nation
Gross domestic product	AUS$/M/yr		36,823 (1)	379,195 (1)
- Change from 1989 to 1990	%		10.4 (2)	9.2 (2)
Population			1,665,900 (2)	17,335,900
Busselton		13,531 (3)		
Bunbury		25,662 (3)		
Capel		4,931 (3)		
Population Growth rate	%/yr		2.00 (4)	1.47
Busselton		3.00		
Capital value	AUS$			
- Growth rate	%/yr			
Agricultural area	km2			

Source: Australian Bureau of Statistics.
(1) 1989-90 value for Western Australia.
(2) % change since previous year, 1990-91 data.
(3) 1991 census value.
(4) 1990-91 estimate.

Certain settler-historic buildings and aboriginal sacred sites have a cultural and historic value that is greater than their simple asset value. Such heritage attributes can be assessed using uniqueness and other criteria, although this is a far from simple process (Pearce et al., 1991).

Second, the cultural differences between aborigines and European settlers highlight the Eurocentric view on which the Common Methodology is grounded. Aboriginal people have lived in Western Australia for at least 50,000 years. During this time, they have witnessed profound environmental changes, including a sea level rise of on the order of 150 meters. As a result of their culture, the relationship between aborigines and the natural environment is apparently more pragmatic than the European view of sea level rise and climate change. Such views should be included in formulating response strategies to sea level rise in Western Australia.

TOURISM

In 1990-91, 1 million people visited the Leuwin-Naturaliste subregion. After Perth, it is the most important tourist destination in Western Australia. During the fiscal year 1990–91, visitors to the Southwest spent an estimated AUS $158 million (WATC, 1992).

During 1989-90, 150,000 people visited Busselton—72,000 in hotels and guest houses, and 78,000 in caravan parks (WATC, 1991). The number of tourists using caravan parks have remained relatively stable over the past 5 years. In contrast, the number of hotel guests increased by 75 percent between 1985 and 1990, which is reflected by an 80 percent increase in the number of hotel beds during the same period (WATC, 1991).

One of the main reasons visitors come to the region is the beauty of its coastal environment. Tourism expenditures thus give a surrogate measure of the "value" of the coastal zone in its present condition. Given the importance of coastal vacationers to many countries in both the developed and the developing worlds, the value of tourism should be included in any revised Common Methodology.

DEVELOPMENT OF A REGIONAL RESPONSE STRATEGY

A major difficulty in implementing an integrated response strategy to sea level rise in Western Australia is the problem of incorporating issues from the international, national, and state arenas into the regional planning process. This bottleneck in information flow is compounded by the gulf between the assessment of potential sea level rise impacts and the formulation of response strategies to mitigate such impacts in Western Australia. Any assessment procedure would reside within an existing process of regional planning, described below.

We have chosen to focus on the regional to local planning process because an integrated, strategic approach is taken that crosses government departments and involves both public and political consultations. Many of these departments have their own strategic plans, but none has the formal integrating role of the Department of Planning and Urban Development in Western Australia.

The present South West Strategy, a planning document covering the whole of the South West, already takes the climate change issue into account (SWDA, 1991) as one of the 14 issues within the environment section, which is one of 10 major subject areas addressed in the strategy. The wording of the issue statement is: "Climatic change and its impact on the region as a whole." Other issue statements of relevance include:

> - preservation of the natural environment in the face of increased population pressures,
> - maintaining access to, and use of, the coast
> - the preservation of lifestyle values....
>
> Ensure that the effects of anticipated environmental change are anticipated and taken into account in the planning and development of coastal and estuarine areas (Strategy 4—The Environment).

The mechanisms for incorporating sea level rise issues into this process are included in Figure 5. This, together with an outline of the regional planning process itself (Figure 6), clarifies many of the differences in approach to the sea level rise problem that have made applying the Common Methodology to Western Australia so difficult.

Planning in Australia has traditionally been based on the British town planning system. This is still the basis for urban planning in Australia (and the United Kingdom), but was seen to be ineffective in Western Australian rural areas outside the metropolitan centers (WA, 1984). In 1987, Regional Planning Committees were established (WA, 1987) to implement a more effective planning framework through a series of regional plans. The South West is one of nine regions in the state that "have been defined to promote overall strategic planning needs in terms of the economic and social needs of the regions" (Klem, 1988).

Regional plans are based on policy-driven, resource-based planning, and not the traditional town planning model. They identify broad environmental and human constraints to the development of a region. "Normal" statutory planning, such as subdivision and zoning of land, is processed within a broad nonstatutory planning framework. Although the regional plans are nonstatutory, they are nevertheless powerful policy-formulation documents because of the community and political backing they receive during their creation and subsequent implementation.

FIGURE 5. APPLYING THE SEA LEVEL RISE ISSUE TO THE REGIONAL PLANNING PROCESS[1]

STAGE[2]	STAGE DESCRIPTION	CONTEXT (sea-level rise as one of a range of issues)
1	Define the Study and Planning Region.	Geographe Bay. (Seaward to the 30m isobath and inland approx. 1km.)
2	Collect Information and Undertake Research.	Climatic change - flood mitigation - physical evidence - vulnerability.
3	Involve the Community Throughout the Study.	Acceptance that sea-level rise is an issue?
4	Identify Trends, Issues and Values.	High social value of coastal zone.
5	Assess Community Needs.	Relative value of recreational/tourist resource (annual holiday destination for large numbers of Perth residents) with health, housing, law and order etc.
6	Identify Opportunities and Constraints.	Opportunities for coastal development if sea-level rise not an issue. Constraint to development if major issue.
7	Formulate Goals and Objectives.	Clear statement of direction on sea-level rise impact mitigation.
8	Identify and Evaluate Strategies to Achieve Objectives.	Draft policy formulation. Valuation techniques - (CBA/Risk Assessment) - Socio-economic/socio-political conditions.
9	Formulate the Preferred Plan.	
10	Obtain Approval for the Plan.	Political and community consultation.
11	Assess Priorities and Prepare Implementation Programmes.	Detailed policy formulation. Allocation of resources to meet objectives (political commitment).
12	Prepare a Policy Statement.	Detailed policy formulation.
13	Monitor and Evaluate Results.	On-going research/community and across Government consultation/on-going funding.
14	Review and Update the Regional Plan.	

[1] Assuming sea level rise is identified as an issue in the process.

[2] All stages can have an interaction component.

FIGURE 6. LOCATION OF FIVE DETAILED STUDY STRIPS

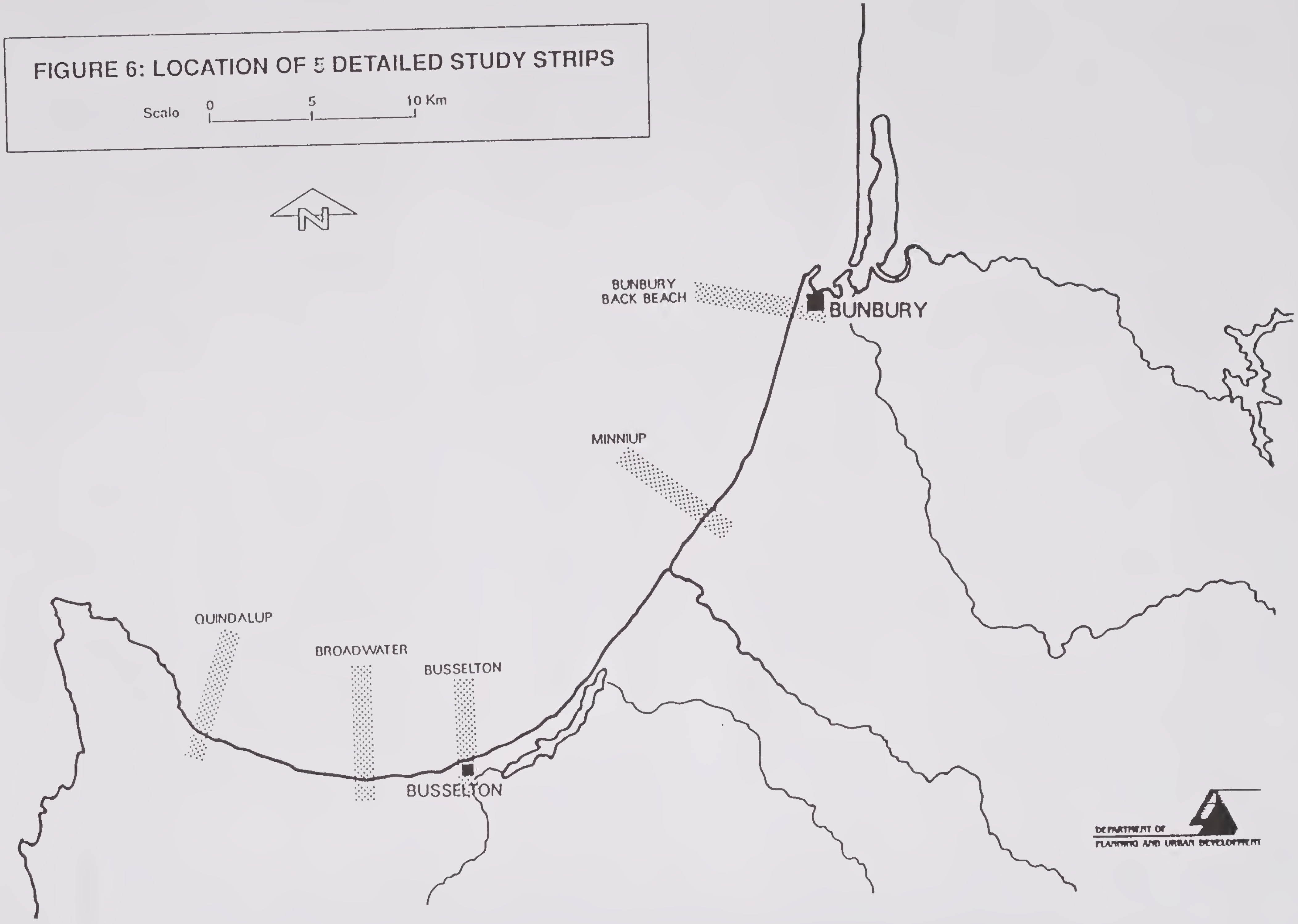


FIGURE 6: LOCATION OF 5 DETAILED STUDY STRIPS
Scalo 0 5 10 Km
N
BUNBURY BACK BEACH
BUNBURY
MINNIUP
QUINDALUP
BROADWATER
BUSSELTON
BUSSELTON
DEPARTMENT OF PLANNING AND URBAN DEVELOPMENT

OUTCOMES

There is a crucial step between the assessment of potential sea level rise impacts and the formulation of policy responses to reduce such impacts. The IPCC Common Methodology apparently assumes that this step is small—that response formulation is a natural progression from the assessment procedure. However, this is *not* the case for Western Australia. Instead, a wide-ranging policy formulation process that includes a full public and political consultation process leads to strategic decisions on coastal zone management. Strategic coastal engineering decisions are essentially embedded within the state and regional planning process.

Therefore, the "Protect" option for responding to sea level rise will be evaluated within a planning process that inherently places higher priority on the "Retreat" and/or "Accommodate" options. However, strict application of the Common Methodology suggests that the Protect option is appropriate for much of the southern section of Geographe Bay (Tables 5 and 9). This is due to the ease of collection of property, land value, and sea defense cost data, in relation to the availability of more complex economic and environmental economic data needed for an extended cost-benefit assessment procedure appropriate for Western Australia. Inclusion of such data would bring the assessment and response strategy formulation processes closer together.

TABLE 9. RESPONSE STRATEGIES: SPECIFICATIONS AND COSTS

Type of stategy	Units	Quindalup	Broadwater	Busselton	Minninup	Bunbury
Retreat (R)						
- people transferred						
- cost of transfer	AUS$					
Accommodation (A)						
- adaption costs (capital)	AUS$					
- drinking water						
- sewerage water						
- drainage upgrading						
- land elevation						
- adaption costs (production)	AUS$/yr					
- agriculture						
- tourism						
- industry						
- fisheries						
Protection (P)						
- upgrading existing defences	AUS$ (1)					
- new defences	AUS$/km	17000 (2)	17000 (3)	17000 (3)	n/a (3)	25,000-50,000
- volume of beach nourishment	Mm3/yr	n/a	n/a	n/a	n/a	5,000-10,000
- cost of beach nourishment	AUS$	n/a	n/a	n/a	n/a	2,500- 5,000
- Defence type		Filled timber	Filled timber	Filled timber	Retreat	Nourishment

(1) None planned or deemed likely by the Department of Marine and Harbours. Appropriate mehod given at cost of new defences

(2) 60m timber groynes filled with sand. Top elevation at shoreline 2.4m above mean-sea-level

It must be stressed that this planning process involves a high degree of public involvement through a number of consultation phases. If the community does not perceive sea level rise and climate change to be an important issue in relation to other regional planning and environmental issues—such as soil and water degradation, unemployment, and the provision of housing—policies for mitigating the impacts of sea level rise may not even be considered by policymakers. In this case, the response strategies would thus be biased toward reactive policies implemented after erosion or storms have caused damage.

Undertaking an IPCC case study using the Common Methodology has been a valuable and interesting exercise for participants in the workshop and the contributors of statistics. There have been numerous comments that the appraisal of their sections of the Common Methodology has made them more aware of the practicalities of implementing strategies to mitigate the potential future impacts of sea level rise and climate change.

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IMPACTS OF SEA LEVEL RISE ON ROCHEFORT SUR MER

Christian Auger
Ministère de l'Environnement/SRETIE
Neuilly sur Seine, France

SUMMARY

This general study of the French coastal area facing the predicted sea level rise cost 400,000 French francs, or about $72,000 (U.S.). The study took into account the impacts of a sea level rise on beach erosion, on the tourist economy, on commercial ports, and, in particular, on the region called Rochefort sur Mer, in the French district Charente-Maritime.

The study compares two responses to sea level rise: doing nothing and taking measures. It was beyond the scope of study to consider all the impacts of sea level rise on France's 3,000-km-long coastline. A complete assessment of all the long-term consequences and of protective measures can only be realized through a case-by-case study of each threatened sector.

This study also showed how difficult it is to define the potential protective and planning measures that may be implemented. Assuming a 0.5-meter rise in sea level and a do-nothing response, 100 percent of local marshes of Rochefort sur Mer (or a 365 km^2 area) will become unusable as soon as the first dams are submerged. Therefore, a passive strategy would cost 167.5 million francs, excluding any capital costs, for *each* flood, and Rochefort sur Mer is likely to be subjected to several floods a year.

The protective strategy of constructing dams and raising existing locks would cost 640 million French francs in the Rochefort region. Thus, the cost of a protective strategy would equal the cost of a passive strategy after four floods.

The choice of one of these two strategies will depend on technical, economic, and ecological considerations. For example, in the next 30–50 years, additional construction work must be undertaken on dams to protect the currently urbanized marshes. Moreover, measures for reducing the urbanization of the marshes in the long term are absolutely necessary.

THE STUDY AREA

The region of Rochefort sur Mer covers an area 362 km^2. It is comprised of many marshes that have been progressively recovered from former bays. Some islands protect the coast against tidal surges and protect the inland bays against high currents.

The town of Rochefort is a former island that quickly became too small and extended itself onto the peripheral marshes. The population is mainly concentrated on the former chalky islands.

The continental coastline is fragile and easily eroded. It is characterized by:

- Muddy foreshore, limited by a straight sandy area.
- Sea cliffs of soft limestone.
- Sandy bands protecting marshes.

The economic activities in the Rochefort region include:

- Rochefort and Brouage-Marennes marshes: Agriculture, including bovine stock farming and cereal production.
- Seudre right bank: Oyster farming, multiculture, aquaculture, and fishing.
- Trade and industry, in coordination with Rochefort commercial harbor.
- Tourism.

The coastline is constantly changing, with some areas highly vulnerable to erosion, and others naturally advancing toward the sea. In general, marshes are lower and are now located at a level of about 2–3 meters CM. The sites in the study area that are more vulnerable to erosion and submersion are the sandy area of Yves marshes and the shingly area of the town of Yves.

VARIATIONS IN SEA AND RIVER LEVELS

The level of the Charentes River varies considerably, and the sea level is also highly variable. For example, during spring tides, high and low tides differ by 7.3 meters.

REFERENCE MARKS

For assessing the variations in sea level, we talk about "zéro des cartes marines" (CM), or the zero point of marine maps. That point is the lowest level reached in case of low tide with a 120 tidal coefficient.

The National Geographic Institute also defines the "zéro des cartes," zero point of land maps, for assessing land altitude. In the Rochefort region, this point is located 3.55 meters over the zero point of marine maps.

WATER LEVEL AND TIDES

During high tide, sea level in Rochefort is 0.2 meters above sea level. For a 115 tidal coefficient, sea level rise will be 7 meters CM along the coastline and 7.2 meters CM in Rochefort.

The highest tide number remains unforeseeable and varies every year because of its dependence on the sun, moon, and earth's positions. In 1991, for instance, there were several tides higher than or equal to a 105 tidal coefficient, endangering the dams protecting the marshes.

EXTRAORDINARY EVENTS

Three extraordinary events occurred in 1971, 1982, and 1985:

- On January 26–27, 1971, the Charente River was not flooded. The tidal coefficients were 84 and 90. Maximal wind speed was about 115 km/h, with a low atmospheric pressure, or 997 mb. However, Beaume and Mastrou marshes, located near Rochefort, were submerged.

- On April 6, 1985, another important submersion occurred. The average river flow was 100 m^3/sec., but the tidal coefficients were 116 and 117, the wind speed was 112 km/h, and the atmospheric pressure was 999.6 Mb (three determining factors). Again, Beaume and Mastrou marshes were submerged (7.35 CM).

- On December 24, 1982, the Charentes River was exceptionally flooded. The tidal coefficients were 45 and 50. However, no submersion was reported in Rochefort.

So, even without the river flooding, a high wind speed and low atmospheric pressure can submerge the dams. And a rise in the river level alone does not necessarily endanger the town of Rochefort. Nevertheless, sea level rise will increase flooding and the sea's advance toward the lowlands.

STUDY ASSUMPTIONS

On April 6, 1985, the registered flooding water level was 10 cm (without any flooding in the river). On January 26 and 27, 1971, the registered level was 85 cm, again without any river flooding, but with unfavorable winds and atmospheric pressure.

The critical water level for submerging marshes around the town of Rochefort is 7.35 meters CM. Along the coast, the critical level of the sea is 7.35 – 0.20 = 7.15 meters CM. However, because of the possibility of a residual surge coming from the sea with an average trough of 0.6 meters, we should add 0.3 meters to this first critical level. This means that any unprotected land or any dam located at 7.45 CM level could be submerged.

Twice within the last 20 years the respective levels of 7.35 and 7.45 meters CM have been registered in Rochefort and on the coastline. A 0.5-meter rise in sea level would considerably increase the frequencies of these phenomena, especially when accompanied by unfavorable winds and atmospheric conditions and the rise in the level of the river).

IMPACTS OF RESPONSES TO A 0.5-METER RISE

The region of Rochefort sur Mer could use two strategies to respond to sea level rise:

- *A passive strategy*: Take no action to restrict the landward advance of the sea.
- *A protective strategy*: Construct, raise, or modify dams and structures.

IMPACTS OF A PASSIVE RESPONSE

IMPACTS ON TOURISM

The impacts on tourism are based on the following hypotheses:

- The beaches of the study area are, on average, 50 meters wide. According to the Bruun rule, a sea level rise of 0.5 meters would flood the entire beach.
- Beaches will not be extended or located in another place.
- The lack of beaches will reduce annual tourist visits by 30 percent.

The annual gross profit from tourism in Rochefort is 221 million francs. Considering a 30 percent decrease in tourist visits, the effective cost of this change would be a loss of 66.3 million francs, and about 1,500 jobs that depend on tourism.

IMPACTS ON MARSHES

Marshes are generally protected by earthen dams of about 7.5/8.0 meters (CM) high. If these dams were destroyed, lands located below 7.55 meters CM could be flooded. Therefore, the height of the protected marshes ranges only from 5.5 to 6.1 meters CM.

Considering their altitude, all marshes of the study area are vulnerable to flooding. They provide a high number of channels for evacuating fresh water toward the sea at low tide. Their submersion would only occur during high tide after the submersion of dams and locks. The maximum height of locks is 7.5 meters CM. So the flooding would first occur through the locks, then through the channels. Considering a critical level of 7.35 meters CM in Rochefort, an additional rise of only 0.15 meters would submerge the dams. Regarding the coastline, a critical level of 7.45 meters CM, and an additional rise of only 0.05 meters would flood the lowest dams.

The vulnerability also stems from the materials used for constructing dams and barriers. Earthen dams will be swept away by the current in case of a brutal sea advance. And major damages could not be repaired within 12 hours (between two high tides). So the next high tide would increase the damage, even in case of an inferior tidal coefficient. Such a hypothesis shows that a passive strategy for responding to an accelerated rise in sea level would increasingly damage Rochefort's dams.

IMPACTS ON AGRICULTURE

The local agriculture is characterized by the cultivation of fodder crops and grain and extensive stock farming.

Progressively, the marshes' exploitation will be aggravated by risks of temporary and permanent flooding and by increasing the salinity of the soil (arising from frequent flooding). Currently, intensive agriculture and marsh draining are the least expensive solutions used by a growing number of farmers to respond to these difficulties. So important socioeconomic changes will be brought about by these activities.

Currently, the marshes protected by dams represent a freshwater reserve dedicated to agricultural activities. In the case of a passive strategy, these lands would be reclaimed by the sea. The potential loss of lands has been assessed as follows :

- Drained lands dedicated to agriculture: 3,500 ha.
- Undrained lands dedicated to agriculture: 1,000 ha.
- Value of a drained hectare of marsh land: 20,000–25,000 francs.
- Value of an undrained hectare of marsh land: 6,000–10,000 francs.

Thus, the estimated lost capital is:

- 3,500 ha x 20,000 FF = 70 million francs.
- 3,500 ha x 25,000 FF = 87.5 million francs.
- 1,000 ha x 6,000 FF = 6 million francs.
- 1,000 ha x 10,000 FF = 10 million francs.

In addition to these financial losses, unemployment will rise. About 500 farms will be threatened by flooding, each employing an average of 1.3 people. Thus, 650 people may lose their jobs.

IMPACTS ON OYSTER CULTURE

A high proportion of oyster culture in the Rochefort region is provided by the marshes. Oysters that have been previously cultivated in the sea are left in 300–500-meter basins before their marketing. These basins dug in marshes are supplied with salt water through channels and locks; other channels are dedicated to freshwater evacuation.

With sea level rise, basins would be completely submerged, impeding the maturation of the oysters. Oyster farmers would be obliged to find other basins in vacant higher marshes (a solution that would result in a progressively shrinking availability of land).

The financial impacts of sea level rise seem to be rather insignificant for oyster farming, and the importance of the costs generated by dams and other protective structures has not been assessed.

For the moment, the least expensive response to a 0.5-meter rise in sea level would be to raise the dams instead of installing other basins and channels. Moreover, oyster farming installations (farm buildings and access ways) are generally usable for only 100 years, which means that their reconstruction will depend on sea level rise. So, the 2.000 oyster farms of the Rochefort region will be only slightly affected by a 0.5-meter rise in sea level.

IMPACTS ON WATER RESOURCES

In the case of regular submersion of the dams and flooding of the marshes, a sea level rise could seriously threaten freshwater resources. The major freshwater catchment point for the Rochefort region is located on the Charente River upstream of a dam protecting against saltwater penetration. A 0.5-meter rise would not endanger this catchment. However, another water catchment point, which at times has been stopped because of saltwater intrusion, is highly vulnerable. This catchment supplies Rochefort with 12 percent of its freshwater consumption; Chatelaillion, with 100 percent; and Fouras, with 50 percent. In addition, Marennes and

Bourcefranc receive 40 percent of their fresh water from a station that will be totally unusable after a 0.5-meter rise in sea level.

According to current assessments, 43.500 people in Rochefort will have to be supplied with fresh water next summer. With a 0.5-meter rise, current installations will be abandoned and future pumping stations will have to be located far from the sea's reach. Canals will need to be constructed to connect towns to the major water pumping station. The installation cost will be as follows:

60 km canalization x 20,000 francs/linear meter = 120 million francs

It should be noted that a protective strategy will cause saltwater intrusion. The volume of salt penetration in fresh water will be assessed in future studies.

IMPACTS ON THE TOWN OF ROCHEFORT

Rochefort's vulnerability stems from its location. It is mainly built on a chalky tableland that quickly became too small and extended itself onto the marshes. The lowest districts are vulnerable to flooding. In the case of a 7.85-meter CM (7.35 meters CM + 0.5 meters) sea level rise, the dams protecting the marshes of the Rochefort region will be submerged during high tides. Moreover, the risk of flooding risks will increase considerably, approaching 55 floods a year.

The buildings and marshes around Rochefort as well as some infrastructure will be flooded and possibly destroyed. They include:

- The aeronautical and aeroclub base.
- The water treatment plant.
- The arsenal industrial area.
- The Corderie Royale Building (an administrative building).
- Installations of the commercial harbor and marina.

The French Ministry of Environment has conducted major assessments of the costs and risks of sea level rise, and published the results in its "Plan d'Exposition aux Risques" (PER).

Urban Zones

An average 0.25-meter sea level rise in flooded districts would result in a 7 percent loss in installations. Using an approximate value of 7 MF/built ha, generated costs would amount to:

51 ha x 7% x 7 MF = 25 MF for each submersion

Moreover the local tertiary sector is also threatened: PER assessed a 2 percent loss in the gross profit of tertiary industries. The annual gross profit/ha of tertiary industries located around local towns amounts to 1.2 million francs. So each flooding, would involve a 1.2 MF cost.

Arsenal Industrial Zone

This zone covers 36 hectares. A 0.25-meter rise would result in an 8 percent loss of current installations—that is, 9 MF/ha or a total of 20.2 MF (36 ha x 8% x 9 MF). Each flood results in a 5 percent loss in gross profits. Assuming annual gross profits of 25 MF/ha, the annual cost of a 0.25-meter rise would be 45 MF. Thus, total losses in the arsenal industrial zone would be 65.2 MF.

La Corderie Royale

Measuring 374 meters long, this installation was built in 1666. Currently an administrative center, it is the most famous building in the region since its recent restoration. The damage from flooding of this historic landmark could not be assessed because of its historical and sentimental values.

Aeronautical Base

The aeronautical base covers 90 hectares. It includes military installations, as well as living quarters for the military staff and their family.

The potential damages resulting from a rise in sea level are not clearly assessed. Indeed, the values of the installations, materials, and stocks on the base remain hardly known.

The Commercial Harbor

The port of Rochefort and the corresponding installations stretch along 20 hectares (including quays, warehouses, services, and basins). The average height of these installations is 7.35 M CM. With a 0.5-meter rise, the high-tide level will reach 7.75 meters.

Assuming a 0.4-meter advance of the sea, PER forecasted a 19 percent loss of the current installations along the harbor. Applying a value of 9 MF/ha, total damages would amount to :

20 ha x 19% x 9 MF = 34.2 MF for only one flood

Under the same conditions, the loss in gross profits would be 8 percent. For an annual gross profit/hectare of 25 MF, one flood would result in a loss of 40 million francs. The total damages for the commercial harbor would amount to 74.2 million francs.

The Marina

Damages to the marina would be difficult to assess for each flood. Material damages amount to about 1 million francs, and would mainly affect repair shops and ships on land. In addition, the loss in gross profits from each flood would approach 0.9 million francs. The total loss from each flood would amount to 1.9 million francs.

TABLE 1. COST PER FLOOD OF TAKING NO ACTION

Urban zone	Loss in capital	25 MF
	Loss in gross profit	1.2 MF
Arsenal industrial zone	Loss in capital	20.2 MF
	Loss in gross profit	45 MF
Commercial port	Loss in capital	34.2 MF
	Loss in gross profit	40 MF
Marina	Loss in capital	1 MF
	Loss in gross profit	0.9 MF
	TOTAL	*167.5 MF*

COSTS OF A PROTECTIVE RESPONSE

PROTECTING AGAINST BEACH EROSION

Two methods can be used simultaneously or separately to protect against beach erosion: (1) beach nourishment with additional sand, and (2) construction of groins.

Beach Nourishment

Protecting against beach erosion would necessitate an annual supply of sand amounting to five times the sand volume consumed by the sea. Assuming that some beaches are naturally supplied with sand, the given volume is an average estimation for the local beaches. With a 0.5-meter rise in sea level, the beach would recede by 50 meters, according to the Bruun rule.

Beaches comprise 65 km of the study area. The price of beach sand, including transportation, is 170 FF/m^3. So, the procedure for estimating the cost of protecting the beach against erosion is:

Sand lost to erosion: 6,500 m x 0.5 m x 50 m = 162,500 m^3
Supplied sand: 162,500 x 5 = 812.500 m^3
Estimated cost: 812,500 m^3 x 170 F = 138 million francs

Groin Construction

Such installations would cost 11.500 F/linear meter. Assuming a beach 6,500 meters long, the estimated cost of protection would be 76 million francs.

Annual Expenses for Protecting Beaches

The effective lifetime of these groins is about 20 years, without significant maintenance. Thus, the first of the protective works will need repair while the last are only be finished. Maintenance should be minimal, since the coast is protected from the tidal surges by peripheral islands.

Taking into account a 20-year period, yearly maintenance costs will be as follows:

Beach reconstruction:	about 7 MF
Groin installation:	about 4 MF
Both techniques used simultaneously:	11 MF

RAISING DAMS AND INSTALLING PUMPING STATIONS

Agricultural Marshes

Currently, dams are still sufficiently high to protect against tides, except for some annual flooding tolerated by marsh farmers. So to protect against a 0.5-meter rise, the dams will have to be raised by an equivalent 0.5 meters. Specifically 100 km of dams will have to be raised, which will cost 1,500 FF/linear meter: 100.000 m x 1.500 FF = 150 MF.

The 30 existing locks will also have to be raised for a 0.2 MF/lock cost, or a total expense of 30 x 0.2 MF = 6 MF.

Pumping will be necessary for evacuating fresh water from marshes because the low-tide periods will be shorter, thus decreasing the available time for draining. Pumps will be placed on evacuation channels, so 30 pumping stations (1 pump/lock) will be required. A pumping station includes: pump, shelter, and electricity supply, for a cost of 2 million francs (excluding the costs of maintenance and wear). So the total cost of this operation is: 30 x 2 MF = 60 MF.

Natural Park of Yves Marshes

The Littoral Conservatory (Conservatoire du Littoral) is the owner of Yves Marshes, which are considered as a natural park and a bird migratory area. The Conservatory is deciding between two strategies for protecting the marshes.

The first choice, an adaptive policy, would consist of fixing the sand. The cost would be 20,000 F/year until the total disappearance of this sandy band.

The second solution, damming the marshes to modify their running, would cost 4 MF. This solution would necessitate installing a pumping network for evacuating fresh waters and obtaining a water flow equivalent to the current one. It would represent an 2 million franc investment.

Total Cost of Protecting Marshes

Raising dams:	150 MF
Raising locks:	6 MF
Installing pumping stations	60 MF
Yves Marshes:	6 MF
Total:	*222 MF*

PROTECTION OF THE TOWN OF ROCHEFORT

Two types of protective measures are to be taken: (1) raising existing dams and (2) constructing new dams.

Raising Existing Dams

To ensure Rochefort protection, 6 km of dams have been constructed. The capital investments needed to raise them amount to 1,500 F/linear meter:

6,000 m x 1,500 F = 9 MF

Constructing New Dams

Unprotected land on the Charente River's left bank now require 14 km of dam construction. Assuming a cost of 10,000 F/linear meter, this operation would cost:

14,000 m x 10,000 F = 140 MF

The Charente River's left bank, which is the location of the aeronautical base, should also be dammed for 4 km. This response would cost:

10,000/linear m x 4,000 m = 40 MF

In addition to these investments must be added the cost of adapting wastewater and rainwater collection networks. A protective strategy requires a permanent evacuation of waste and rain waters. So, to enable these evacuations, in case of high precipitation and high tide, 10 pumping stations are necessary. This would entail an additional investment of 1.5 MF/station (excluding maintenance and wear), amounting to :

10 x 1.5 MF = 15 MF

The total cost of Rochefort's protective strategy is 204 million francs.

TABLE 2. COSTS OF A PROTECTIVE STRATEGY IN ROCHEFORT REGION

Protection of beaches	- Sand supply	138 MF
	- Groin construction	76 MF
Protection of agricultural marshes	- Dam raising	150 MF
	- Lock raising	6 MF
	- Pump installation	60 MF
Protection of Yves Marshes	- Dam construction	4 MF
	- Pump installation	2 MF
Protection of Rochefort town	- Dam raising	9 MF
	- Dam construction	180 MF
	- Pump installation	15 MF
	TOTAL	***640 MF***

CONCLUSION

Two strategies have been chosen as appropriate responses to sea level rise: a passive strategy and a protective strategy.

The protective solution has only been forecasted for a 0.5-meter rise within a 100-year period. No calculations have been made for a longer period. The total cost of a protective strategy would be 640 million francs, which is most likely underestimated.

The passive strategy involves a minimal capital loss of 97 million francs. Moreover, a 120 million franc expense is required for modifying water supply networks and replacing unusable pumping stations (because of salt water intrusion). Both these costs would total 217 million francs.

On the other hand, material losses resulting from each flood would approach 167.5 million francs. Moreover, sea level rise would increase the frequency and destructiveness of floods.

Estimates show that, excluding capital losses, costs originating from only four floods would be equal to all the protective strategy expenses.

So, as a first conclusion, based on the study of this small geographic area, it can be said that a protective strategy seems to be the less expensive solution within a 100-year period. However, implementing one of these solutions or using components of both of them according to priorities also depends on human factors that have not been considered in this study and that will certainly modify the current forecasts.

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IMPACTS OF SEA LEVEL RISE ON JAPANESE COASTAL ZONES AND RESPONSE STRATEGIES

Nobuo Mimura
Department of Urban and Civil Engineering
Ibaraki University
Ibaraki, Japan

Masahiko Isobe
Department of Civil Engineering
University of Tokyo
Tokyo, Japan

Yasushi Hosakawa
Purification Hydraulics Laboratory
Port and Harbor Research Institute
Ministry of Transport, Japan

ABSTRACT

Japan's coastal zones are unique in their highly diverse natural conditions and in the large populations, economic activities, and assets concentrated in these zones. Previous vulnerability assessments have tended to focus on natural coastlines, such as the coral reefs and the deltas of large rivers. However, if it is required to quantitatively assess the impact of global warming and the resulting rise in sea level on a truly worldwide basis, coastal zones of developed nations must be examined.

Sea level rise will have serious impacts on Japanese coastal zones. The "zero-meter altitude zone" as well as the flood-prone zones during storm surges would be expanded significantly. This would endanger human lives and the assets and socioeconomic activities concentrated in the coastal zones, along with the infrastructures that support those activities.

To minimize these potential losses, Japan needs to build protective structures. Costs of ¥10 trillion are estimated for raising existing embankments and other facilities alone. In addition, raising the ground level, reinforcing pump stations, and repairing bridges, waterworks, and sewage facilities will increase the cost.

However, these countermeasures would not necessarily reduce Japan's vulnerability to sea level rise. The more protective structures are built, the more Japan will need to depend on artificial facilities, at the expense of the preservation of natural coasts. In this sense, vulnerability could increase. Therefore, other kinds of means will be necessary to protect the natural coasts.

To strike a proper balance between the development and the preservation of sea coasts and to prepare for the future sea level rise, a comprehensive coastal zone management plan will be an important theme, not only for developing nations, but also for countries like Japan that have highly developed coastal zones.

INTRODUCTION

Sea level rise constitutes a basic physical change in the environment caused by global warming. There is growing concern that it will have grave impacts on coastal zones throughout the world. With this in mind, in October 1990 the Coastal Zone Management Subgroup (CZMS) of the Intergovernmental Panel on Climate Change (IPCC) published a framework for future strategies and the themes to be addressed (IPCC CZMS, 1990). Then in March 1991, the CZMS decided to assess the vulnerability of coastal zones to an acceleration in sea level rise on a worldwide basis to prepare concrete countermeasures. They called on each nation to carry out case studies.

In Japan, various universities, the Japan Society of Civil Engineers, the Japan Federation of Construction Contractors, and governmental administrative branches, such as the Environment Agency and the Ministries of Construction, of Transport, and of Agriculture, Forestry, and Fisheries, have conducted studies on the impacts of global warming, including sea level rise.

In response to the call from the CZMS of the IPCC, the present report summarizes these studies and assesses the vulnerability of Japan's coastal zone to sea level rise. Its objectives are:

1. To determine the impacts of anticipated sea level rise on the entire Japanese coast.
2. To estimate the impacts on the socioeconomic activities of coastal zones, particularly Tokyo's, focusing on the infrastructure of the coastal zones. A case study is carried out in Tokyo in an effort to determine types of impacts of sea level rise on huge cities.
3. To study adaptive response options that could be taken in Japan.

CHARACTERISTICS OF JAPANESE COASTAL ZONES

NATURAL COASTS

The Japanese land mass stretches from the subtropical zone in the south to the subarctic zone in the north, and faces the Pacific to the east and Sea of Japan to the west. Because of these geographic conditions, such external forces as tides and waves vary significantly, depending on the particular location. The total coastline is about 34,390 km, which is very long relative to the size of the land. Typical Japanese coastal features include sandy beaches, gravel beaches, rocky coasts, cliffs, mud flats, coral reefs, and mangrove swamps. Table 1 shows the length and area of each type of natural coast.

TABLE 1. GEOGRAPHICAL FEATURES OF THE JAPANESE COASTLINES

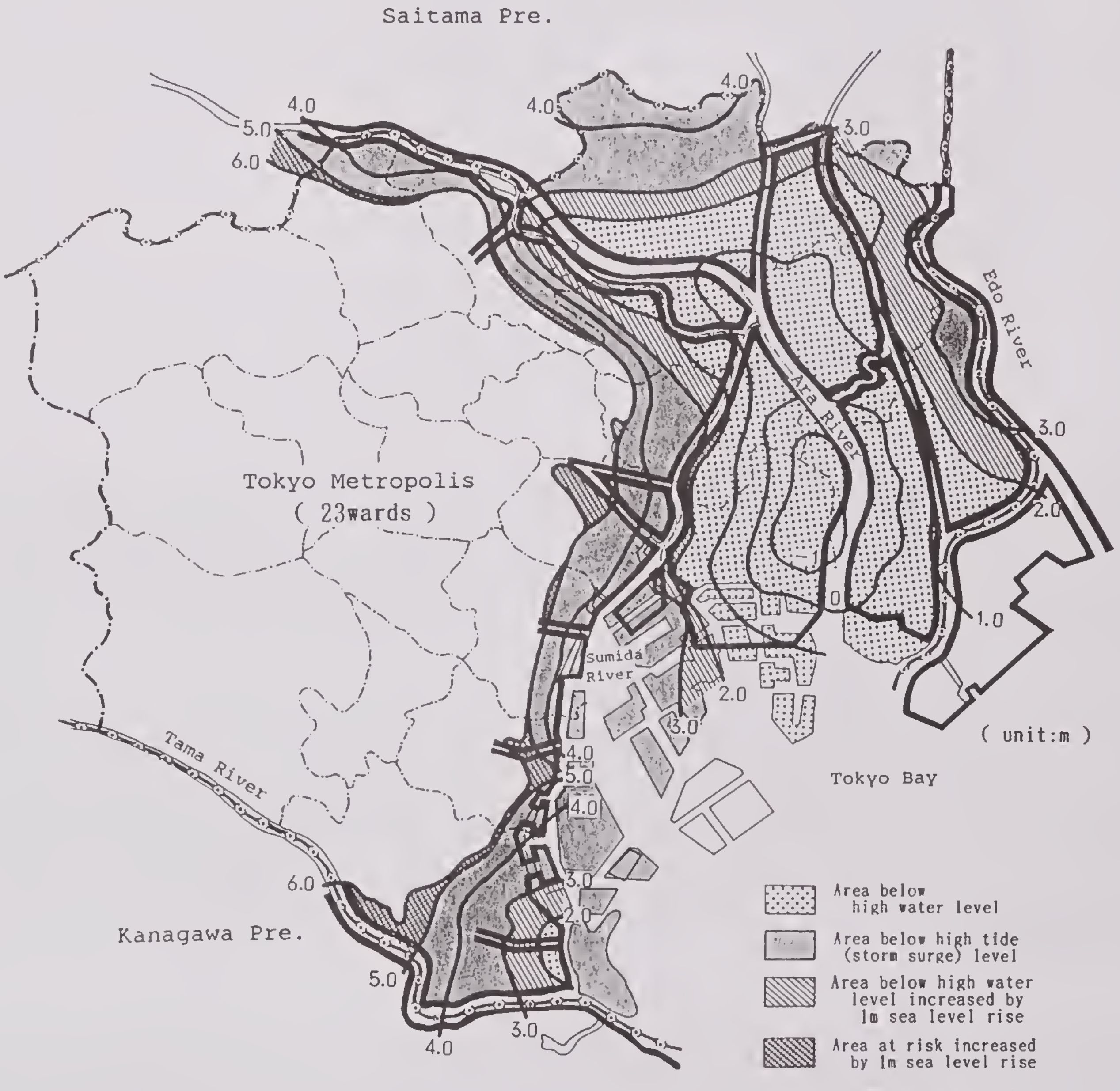
Geographical Features	Length and Area
Natural coast	
Intertidal flat	540 km^2
Sea grass bed	1,370 km^2
Coral reef	879 km^2
Sandy beach	6,700 km
Mud flats, tidal flat	400 km
Rocky coast	6,200 km
Artificial coast	9,320 km
Sea wall	8,800 km
Groin	9,300 groins/400 km
Detached breakwater	630 km
Breakwater	1,100 km
Total length (km)	**34,390**
Total area (km^2)	**2,789**

Sources: Environmental Agency, 1980 and 1989; River Bureau, Ministry of Construction, 1990.

Sandy beaches comprise 24 percent of the Japanese coastline. However, in recent years, these beaches have suffered from increasing erosion: 43 percent have been eroded, only 6 percent have increased their sand dunes, and 41 percent are in stable condition. More than 35 percent of the mud flats, which constitute one of the most important ecosystems in the coastal zones, have disappeared over the past 45 years, owing to vigorous coastal development and landfills. All in all, about 120 km^2 of land have been lost over the past 70 years.

Tokyo, the capital of Japan, has an extremely high concentration of political, economic, and cultural facilities. Its power consumption amounts to 15 x 10^{10} KWH (25 percent of the entire nation), and the city gas consumption, 60 x 10^{12} Kcal (40 percent of the entire nation). Many problems result from this "single-pole concentration," such as poor land availability, access to transportation, and waste disposal. It has been pointed out that Tokyo is in great need of diversifying the concentrated functions. As Figure 1 shows, the eastern half of the 23 Wards in the middle of Tokyo is characterized by low-lying land. Since some of the low land is below sea level at flood tide, and the ground is soft, this area has been vulnerable to disasters.

FIGURE 1. DISTRIBUTION OF LOWLANDS AND POSITIONS OF HIGH-TIDE EMBANKMENTS


Saitama Pre.
4.0
5.0
6.0
4.0
4.0
3.0
Edo River
Ara River
3.0
2.0
Tokyo Metropolis
(23wards)
1.0
Sumida River
2.0
3.0
(unit:m)
Tokyo Bay
Tama River
4.0
5.0
4.0
3.0
2.0
6.0
Kanagawa Pre.
5.0
4.0
3.0
Area below high water level
Area below high tide (storm surge) level
Area below high water level increased by 1m sea level rise
Area at risk increased by 1m sea level rise
Storm surge protection embankment

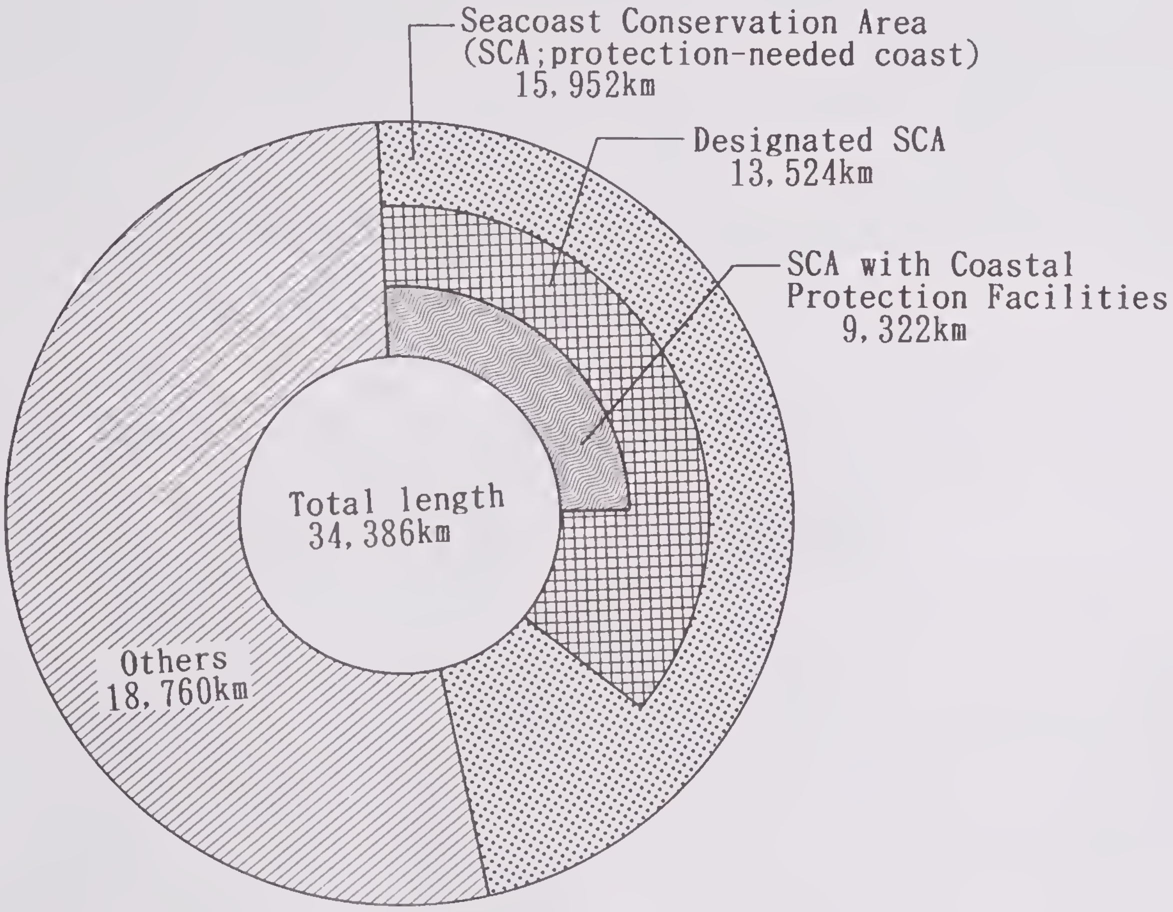
Contour lines in this figure are based on the current low water level. The current high water level is +2.0.

Source: Tokyo Metropolitan Office.

ARTIFICIAL COASTS

A notable feature of the Japanese coast is the increasing length of artificial coastline. Protective structures have been built along 9,320 km, or 27 percent, of the Japanese coast. In addition, about 15,950 km, or 46 percent of the entire Japanese coastline, is designated as needing protective structures. Figure 2 shows the present status of Japanese coastal protection.

FIGURE 2. PRESENT STATUS OF JAPANESE COASTAL PROTECTION (AS OF MARCH 31, 1990)



NATURAL DISASTERS

Japan's coasts suffer from very serious natural disasters. These include earthquakes, typhoons, low atmospheric pressures, and seasonal winds and waves during the winter. Figure 3 shows past records of *tsunami*, storm surges, high waves, and coastal erosion. Table 2 shows examples of disasters caused by storm surges that have occurred over the past 80 years.

BACKGROUND

The Japanese land area is about 377,000 km^2. Since about 72 percent of the area is mountainous, the majority of the population lives in the coastal zone, and the economic activities are concentrated in the flat lands close to the coasts. Figure 4 shows the population distribution in each area. At present, the flood-prone areas constitute 1.5 percent of the total land. About 11 million inhabitants (9.3 percent of the entire population) live here.

FIGURE 3. COASTAL DISASTERS IN JAPAN

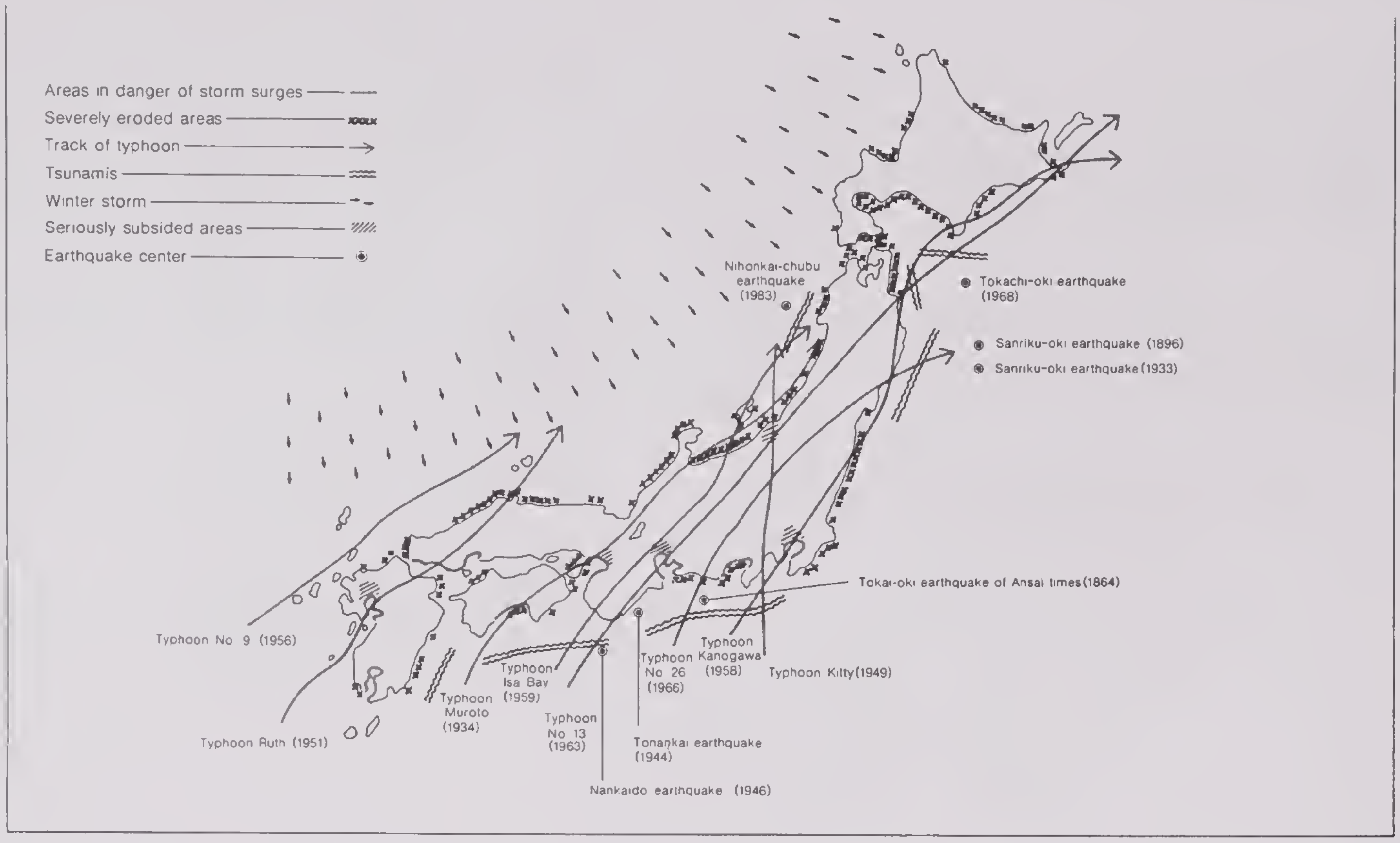
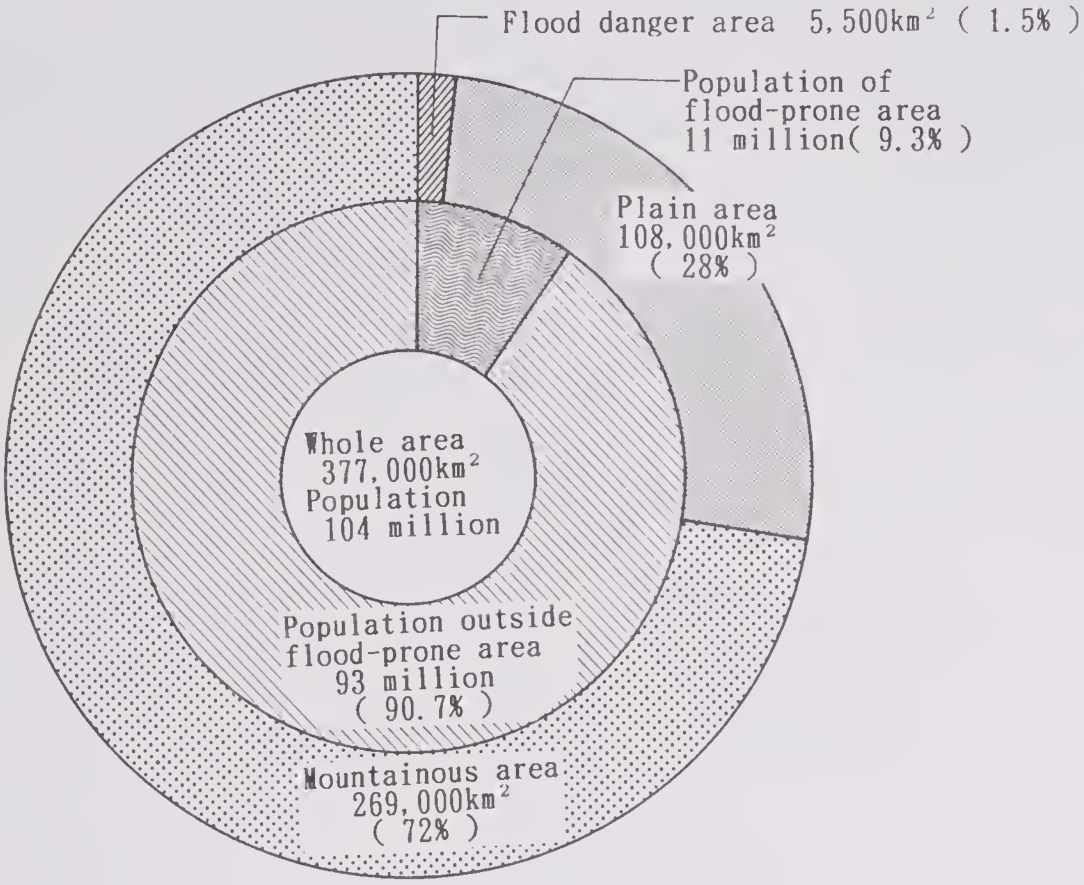


TABLE 2. RECORDS OF NOTABLE STORM SURGE DISASTERS OVER THE PAST 80 YEARS

Date	Major Damaged Area	Highest Water level		Maxmum deviation (m)	Human Casualties			Damage to Houses			Others
		Above Tokyo pail (m)	Above mean high water level of spring tides (m)		Dead	Injured	Missing	Completely destroyed	Partially destroyed	Washed away	
1 Oct,1917	Tokyo Bay	3.0	2.0	2.1	1,127	2,022	197	36,459	21,274	2,442	
13 Sep,1934	Ariake Sea	3.8	1.3	0.9	373	181	66	1,420		791	
21 Sep,1934	Osaka Bay	3.1	2.3	2.9	2,702	14,994	334	38,711	49,257	4,277	Muroto Typhoon
27 Aug,1942	Suo Sea	3.3	1.7	1.7	891	1,438	267	33,283	66,486	2,605	
17 Sep,1945	Southern Kyushu	2.6	1.2	1.6	2,076	2,329	1,046	58,432	55,006	2,546	Makurazaki Typhoon
3 Sep,1950	Osaka Bay	2.7	1.9	2.4	393	26,062	141	17,062	101,792	2.069	Typhoon Jane
14 Oct,1951	Southern Kyushu	2.8	1.5	1.0	572	2,644	371	21,527	47,948	3,178	Typhoon Ruth
25 Sep,1953	All parts of the country	2.6	1.3	1.6	162	5,403	24	4,508	20,047	2,061	Typhoon No.13
27 Sep,1959	Ise Bay	3.9	2.6	3.4	4,697	38,921	401	38,921	113,052	4,703	Ise Bay Typhoon
16 Sep,1961	Osaka Bay	3.0	2.2	2.5	185	3,879	15	13,292	40,954	536	Second Muroto Typhoon
21 Aug,1970	Tosa Bay	3.1	2.4	2.4	12	352	1	3811	3,628	40	Typhoon No.10

FIGURE 4. POPULATION IN FLOOD-PRONE AREAS



Source: Sea Coast Division, River Bureau, Ministry of Construction.

Huge cities like Tokyo, Osaka, and Nagoya are all located in the coastal zones, as are facilities for industrial production, energy production, commerce, fisheries, and recreation. The variety and intensity of land use are high in these areas. Figure 5 shows the concentrations of these various activities for three metropolitan areas that account for more than 50 percent of Japan's industrial production and 70 percent of its national wholesale trade. Moreover, there are about 1,100 harbors and ports, as well as about 2,950 fishing ports, along Japanese coasts.

Recently, land reclamation and the creation of new waterfronts have centered on coasts adjacent to large cities. These projects increase the vulnerability to damage resulting from the sea level rise.

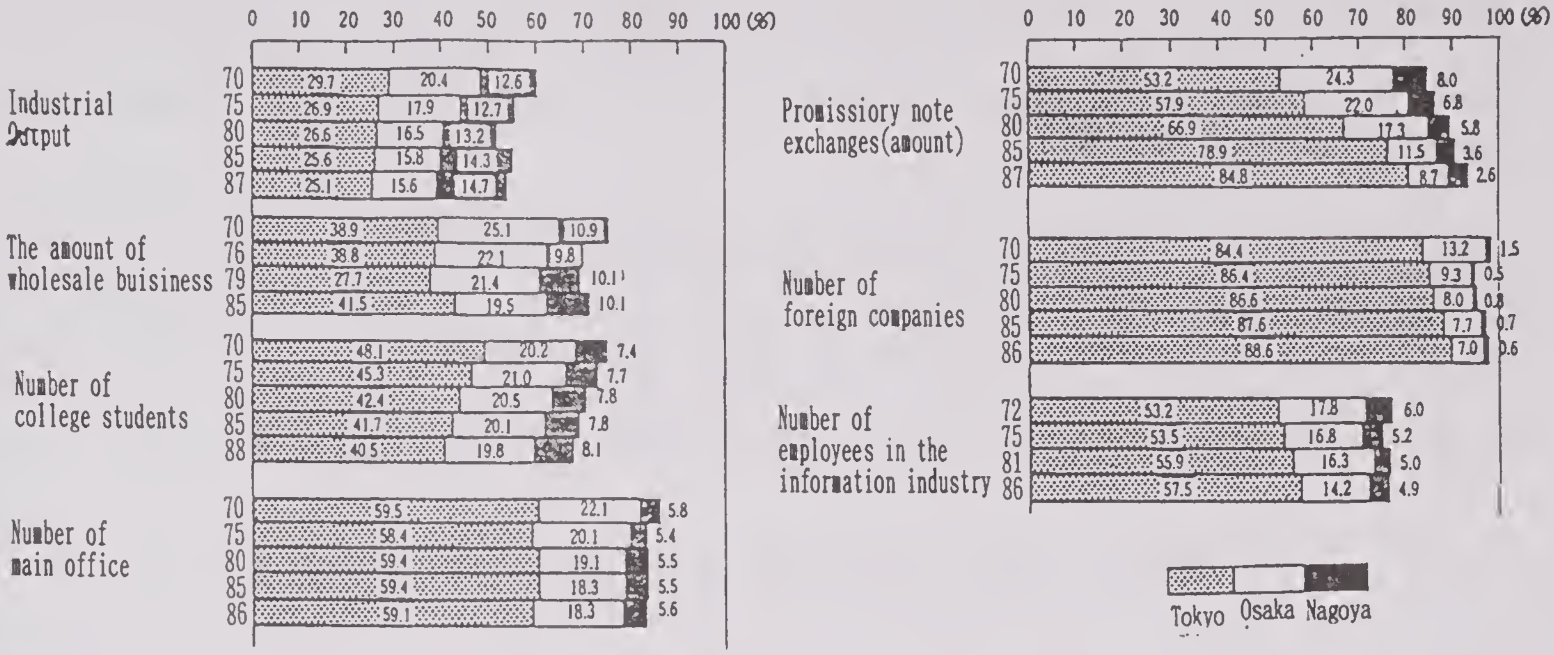
ASSESSMENT METHOD

DATA USED

The increasing risks of inundation and flooding would be the most primary impact of sea level rise. To assess the impact on all of Japan, the socioeconomic impacts have been studied in terms of area, population, and assets (Matsui et al., 1992).

To calculate the area to be inundated or to be flooded, the data of elevation and land use were taken from "Digital National Land Information" (Geographical Survey Institute, National Land Agency). "Population Mesh Data" in the 1985 National Census were used to calculate the population in the flooded area. To calculate assets, the net fixed assets in "National Accounts" (Economic Planning Agency) were used.

FIGURE 5. CONCENTRATION OF ECONOMIC ACTIVITIES IN THREE METROPOLITAN AREAS



Source: National Land Statistical Survey, National Land Agency.

CALCULATION METHOD

In calculating the area below a given water level, since the mesh interval of the altitude data is 250 meters, the entire 250 x 250 m^2 was considered to be flooded, when the altitude of any particular point is below the designated flood height. However, since the altitude is given in 1-meter units, the accuracy of the flood prediction will depend on this resolution of the altitude. The flooded areas were summed individually for each land use type. To calculate population in the flooded area, the population density per km^2 was multiplied by the flooded area. The assets in the flooded area were calculated on the basis of the flooded area and the population distribution in it by assuming that per-capita fixed assets are the same as the average for the entire nation.

SEA LEVEL RISE SCENARIOS FOR WATER LEVEL

In its first report, Working Group I of the IPCC estimated that sea level rise would rise 65 centimeters (30-110 centimeters) before 2100 (IPCC WG1, 1990). Based on this estimate, CZMS proposed two values—0.3 meter and 1 meter—as the scenarios for sea level rise for the present vulnerability assessment. Since previous assessments in Japan were carried out based on many different scenarios, the present study could not follow the proposed scenarios exactly, though the authors tried to follow them where possible.

The mean sea level changes in response to storm surges, waves, and *tsunamis*. Moreover, these changes differ by location. These changes were taken into consideration by each location, when flood-prone areas were calculated. Although the rate of sea level rise is another important factor, its effects were not considered in this study. The climatic changes brought about by global warming are not limited to sea level rise. It has been pointed out that there will also be such phenomena as changes in intensity, frequency, and courses of typhoon, and changes in rainfall. These changes are likely to differ, depending on location. However, the estimates for these changes are still uncertain on a regional or local scale. Accordingly, these factors were not taken into account in this assessment.

Moreover, it has been predicted that it will be several years before the increase in sea level becomes apparent. Until then there must be big changes in both the natural environment and the socioeconomic development along the coasts. However, since it is nearly impossible to anticipate long-term social changes, these long-term changes were not included in the assessment. Thus, the impacts were assessed for the present coastal zone conditions under the assumptions of sudden rises in the sea level of 0.3, 0.5, and 1 meters. These scenarios are shown in Table 3.

TABLE 3. SCENARIOS FOR VULNERABILITY ASSESSMENT AND RELATED ASSUMPTIONS

Boundary Conditions	**Assumptions**
Sea level rise due to global warming	The scenario differs for 0.3 m, 0.5 m, and 1.0 m, depending on each study.
Other climate changes Stronger typhoons Increased frequency of typhoons Typhoon course changes Changes in precipitation and runoff Changes in atmospheric and water temperatures	In principle, it was assumed that the present conditions would remain unchanged. However, changes in these phenomena were considered qualitatively in some parts.
Changes in natural and social conditions	No changes were assumed.

Each scenario corresponds to one of three meteorological conditions (mean-water level, high-water level, high-water level + storm surge or *tsunami*). An area below the high-water level is called a "zero-meter altitude area." Such an area is affected by the sea nearly all the time. An area that will be below the high-tide level during a typhoon or a *tsunami* can be considered a "flood-prone area."

The water level resulting from a storm surge or a *tsunami* differs according to coastal topography. In the present analysis, the coastal zones of the entire nation were divided as follows: the Sea of Japan; the Pacific, North; the Pacific, South; and enclosed bays and inland seas (see Table 4 and Figure 6). The last zone was subdivided into two sections: areas with small tidal ranges (Tokyo Bay, Osaka Bay, and Ise Bay) and areas with large tidal ranges (Seto Inland Sea and Ariake Bay). One of the most important factors in assessing the impacts of sea level rise on each zone is the ground motion. In Japan, owing to changes in the earth's crust or the influence of pumping underground water or natural gas, the ground in each region undergoes complex changes. For example, one city has experienced land subsidence of more than 4 meters over the past 50–60 years.

TABLE 4. WAVE HEIGHT AND TIDAL LEVEL BY LOCALITY

Water Bodies	Design Wave Height (m)	Past Maximum Tide Level (m)	Mean High Water Level (m)
Enclosed bay, Inland sea	1.96	2.50	1.40
Sea of Japan (open bay, exposed coast)	3.31	1.24	0.64
The Pacific, North (open bay, exposed coast)	4.05	3.03	0.63
The Pacific, South (open bay, exposed coast)	3.87	2.06	0.96

Sources: Ministry of Agriculture, Forestry, and Fisheries; Ministry of Transport; and Ministry of Construction (1990).

FIGURE 6. DIVISION OF JAPANESE COASTAL ZONES

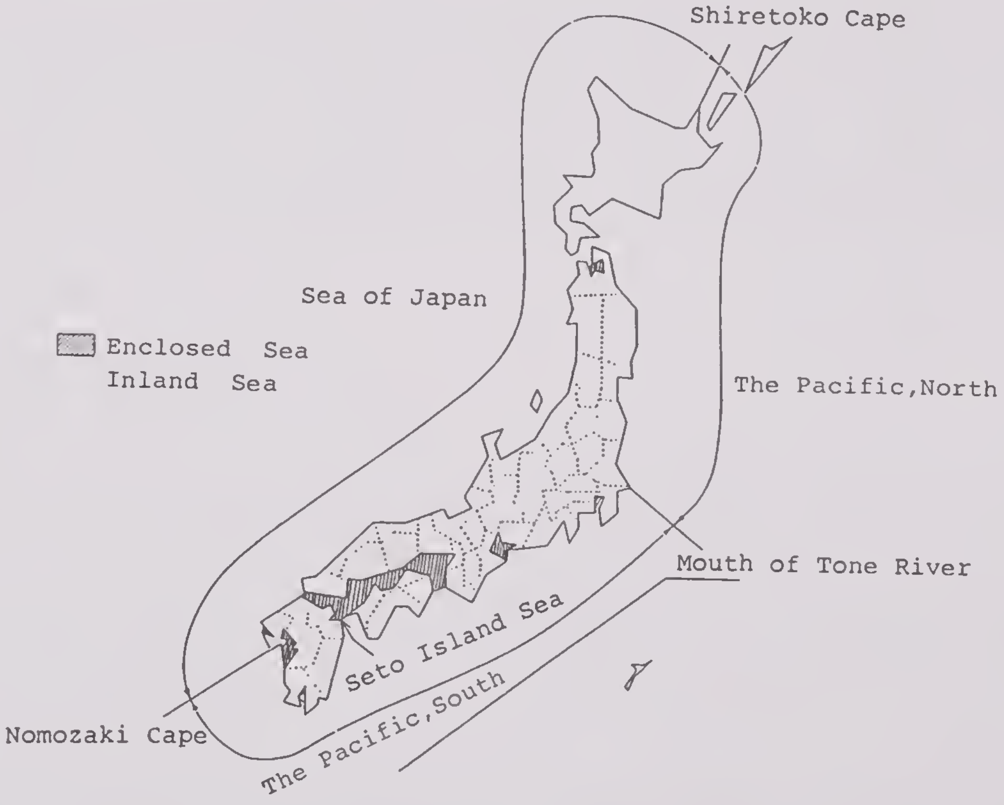


Table 5 shows the scenarios of water levels for these zones. An increase in sea level due to wave setup, which corresponds to 10 percent of the maximum significant wave height, was added to the storm surge. Increases of 0.3, 0.5, and 1 meters would be superimposed over these heights in order to account for the effects of sea level rise.

TABLE 5. SCENARIOS OF WATER LEVELS IN EACH ZONE (IN METERS)

	Meteorological Conditions					
Coastal Zone	*SLR or Mean-Water Level (1)*	*High-Water Level (2)*	*Significant Wave Height (3)*	*Anomaly of Storm Surge or Tsunami (4)*	*High-Water Level (1) + (2)*	*High-Tide Level Storm Surge or Tsunami) (1)+(2)+ (3)*0.1+(4)*
Sea of Japan	0	0.64	5.0	0.6	0.6	1.8
	0.3				0.9	2.1
	0.5				1.1	2.3
	1.0				1.6	2.8
North Pacific	0	0.63	5.5	2.4	0.6	3.6
	0.3				0.9	3.9
	0.5				1.1	4.1
	1.0				1.6	4.6
South Pacific	0	0.96	7.0	1.1	1.0	2.8
	0.3				1.3	3.1
	0.5				1.5	3.3
	1.0				2.0	3.8
Tokyo Bay Osaka Bay Ise Bay	0	0.92	3.0	2.8	0.9	4.0
	0.3				1.2	4.3
	0.5				1.4	4.5
	1.0				1.9	5.0
Seto Inland Sea Ariake Bay	0	1.59	5.0	2.5	1.6	4.6
	0.3				1.9	4.9
	0.5				2.1	5.1
	1.0				2.6	5.6

RESULTS

Table 6 shows the study results. At present, even under normal conditions, areas of about 861 km^2 are below the mean high-water level. About two million people live in this zone, and its assets are ¥54 trillion (U.S. $415 billion). Once the sea level rises by 1 meter, this low-lying zone will expand to 2,340 km^2, or 2.7 times larger than its present size. The population of the enlarged zone will be 4.1 million, with assets worth ¥109 trillion (U.S. $838 billion). Moreover, the flood-prone zone, which is currently 6,270 km^2, will expand to 8,900 km^2 if the sea level rises by 1 meter. More than 15 million people would be endangered.

Since a *tsunami* may locally reach more than 20 meters, the values obtained on an averaged basis shown in Table 5 do not reflect the extreme impact of a tsunami. It should be considered in a different context.

TABLE 6. IMPACTS OF VARIOUS RISES IN SEA LEVEL

	Area to be Flooded (km^2)				**Population at Risk (10,000)**				**Assets at Risk (Trillion Yen)**			
Water Levels	*Present Sea Level*	*0.3 m Rise*	*0.5 m Rise*	*1.0 m Rise*	*Present Sea Level*	*0.3 m Rise*	*0.5 m Rise*	*1.0 m Rise*	*Present Sea Level*	*0.3 m Rise*	*0.5 m Rise*	*1.0 m Rise*
Mean-Water Level	364	411	521	679	102	114	140	178	34	37	44	53
High-Water Level	861	1,192	1,412	2,339	200	252	286	410	54	68	77	109
High-Tide Level (storm surge or *tsunami*)	6,268	6,662	7,583	8,893	1,174	1,230	1,358	1,542	288	302	333	378

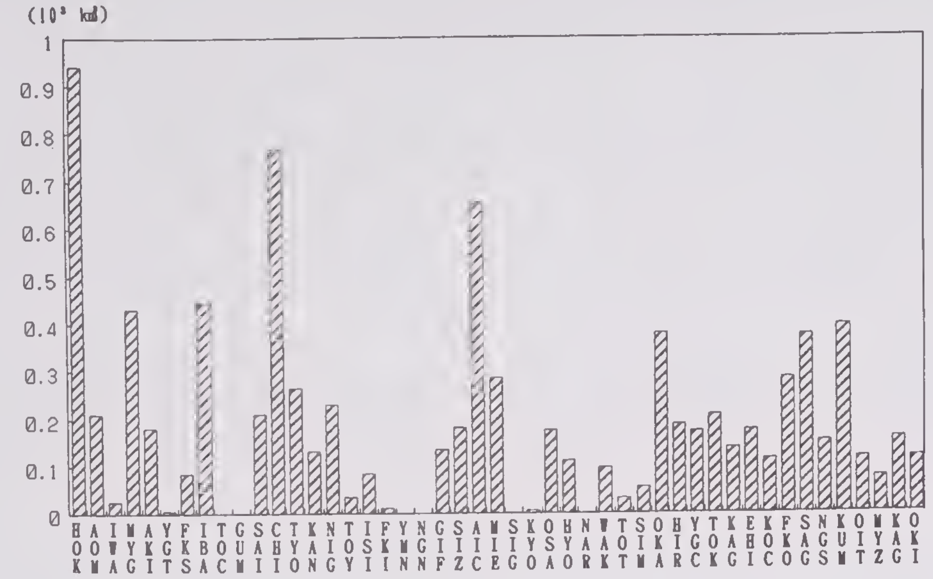
Figure 7 shows the areas, population, and assets in the flood-prone zone by each prefecture. It is only natural that the largest impacts on population and assets are likely to occur in such metropolises as Tokyo, Osaka, and Nagoya. Since Tokyo's water line is protected by high-tide embankments, sea level rise would not cause flooding immediately. However, there is no doubt that the amount of land below the high-water or high-tide (storm surge) level would increase. If the sea level rises by 1 meter, the land area below the high-water level (present high-water level +1 meter) would constitute one-fourth of the 23 Wards, the total area of which is 591.9 km^2. The land below the storm surge level (present high-water level +4 meter), this land area would become as large as the eastern half of these 23 Wards. Though the land area below the storm surge level accounts for only 0.06 percent of the national land, this area supports 3 percent of the total population, 2 percent of total industrial production, and 17 percent of commercial activity. Therefore, the high-tide prevention embankments will become even more important for Tokyo once the sea level rises.

IMPACTS ON INFRASTRUCTURE

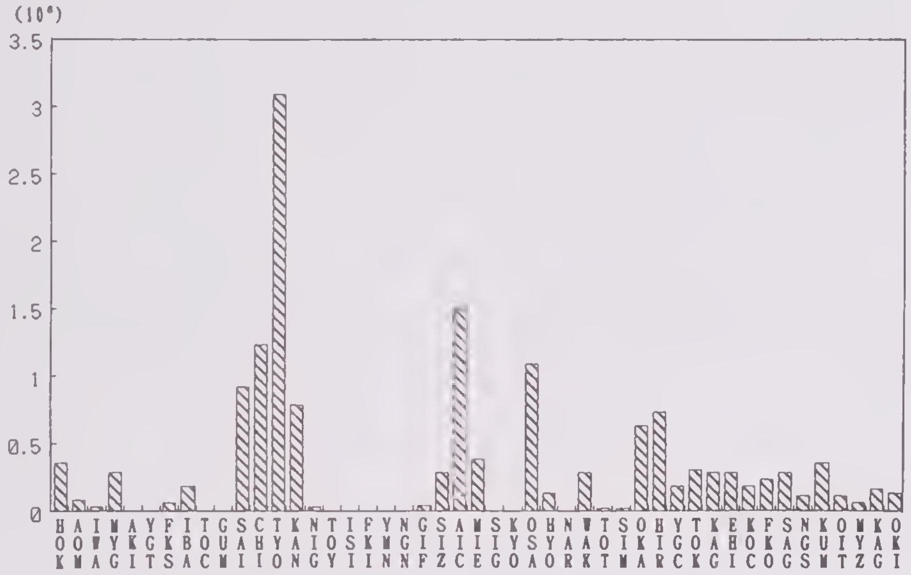
Extensive infrastructure, such as the disaster-prevention systems and transportation facilities, protect and maintain socioeconomic activity in the coastal zones. If a rise in sea level should damage this infrastructure, the impacts would spread to the socioeconomic systems as a whole. Figure 8 provides an overview of how impacts could spread. They would begin at the sea level rise, change the physical phenomena in the coastal zones, and spread to harbors, rivers, and structures on the coasts.

The structures and the facilities are divided into two groups: those located in coastal zones (harbors, river and coastal facilities, etc.) and those located further inshore (roads, railways, airports, underground shopping malls, subways, waterworks, sewage, etc.). Studies have been conducted on the impacts of sea level rise on various aspects of function and safety. Figure 8 shows that the impacts would be significant and widespread. Tables 7–9 shows the summary of the impacts on coastal facilities, and other inland facilities for transportation and energy supply, and daily life.

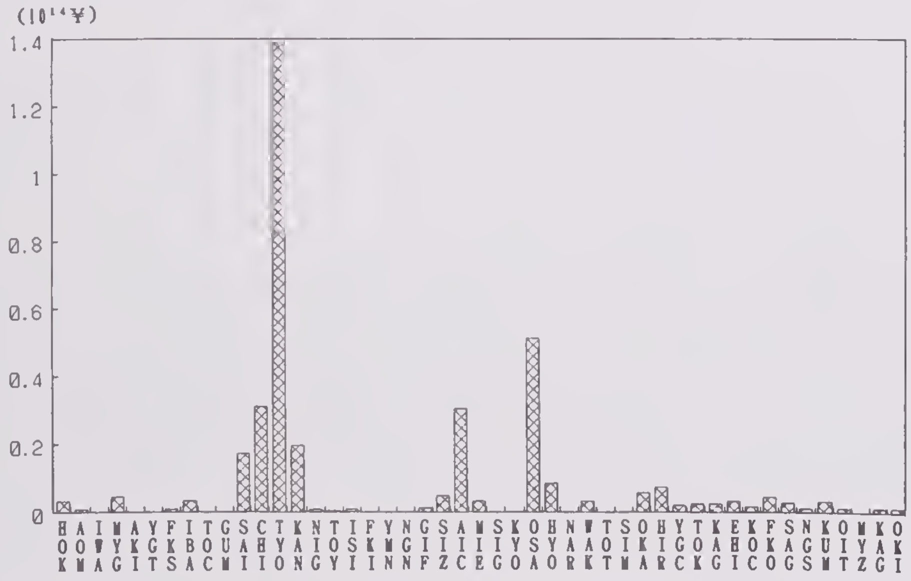
FIGURE 7. IMPACTS OF SEA LEVEL RISE ON EACH PREFECTURE (1 M SLR + STORM SURGE OR *TSUNAMI*)



(a) Area to be flooded

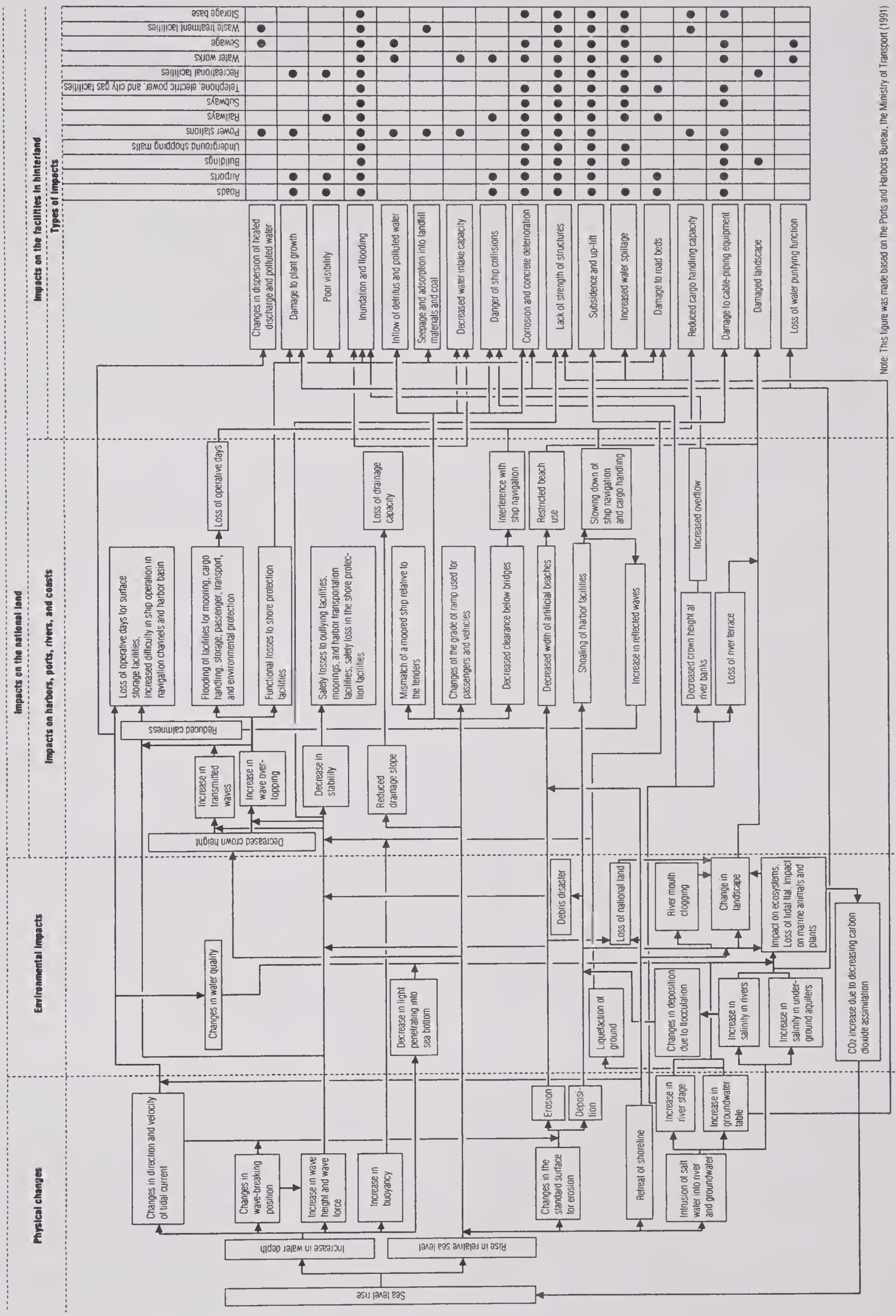


(b) Population at risk



(c) Assets at risk

FIGURE 8. PROPAGATION OF IMPACTS INDUCED BY SEA LEVEL RISE


Physical changes
Environmental impacts
Impacts on the national land
Impacts on harbors, ports, rivers, and coasts
Impacts on the facilities in hinterland
Types of impacts
Sea level rise
Increase in water depth
Rise in relative sea level
Changes in direction and velocity of tidal current
Changes in wave-breaking position
Increase in wave height and wave force
Increase in buoyancy
Changes in the standard surface for erosion
Retreat of shoreline
Intrusion of salt water into river and groundwater
Erosion
Deposition
Increase in river stage
Increase in groundwater table
Changes in water quality
Decrease in light penetrating into sea bottom
Liquefaction of ground
Changes in deposition due to flocculation
Increase in salinity in rivers
Increase in salinity in underground aquifers
CO2 increase due to decreasing carbon dioxide assimilation
Debris disaster
Loss of national land
River mouth clogging
Change in landscape
Impact on ecosystems, Loss of tidal flat. Impact on marine animals and plants
Decreased crown height
Increase in transmitted waves
Increase in wave over-topping
Decrease in stability
Reduced drainage slope
Reduced calmness
Loss of operative days for surface storage facilities. Increased difficulty in ship operation in navigation channels and harbor basin
Flooding of facilities for mooring, cargo handling, storage, passenger, transport, and environmental protection
Functional losses to shore protection facilities
Safety losses to outlying facilities, moorings, and harbor transportation facilities; safety loss in the shore protection facilities
Mismatch of a moored ship relative to the tenders
Changes of the grade of ramp used for passengers and vehicles
Decreased clearance below bridges
Decreased width of artificial beaches
Shoaling of harbor facilities
Increase in reflected waves
Decreased crown height at river banks
Loss of river terrace
Loss of operative days
Loss of drainage capacity
Interference with ship navigation
Restricted beach use
Slowing down of ship navigation and cargo handling
Increased overflow

	Roads	Airports	Buildings	Underground shopping malls	Power stations	Railways	Subways	Telephone, electric power, and city gas facilities	Recreational facilities	Water works	Sewage	Waste treatment facilities	Storage base
Changes in dispersion of heated discharge and polluted water					●						●	●	
Damage to plant growth	●	●			●				●				
Poor visibility	●	●				●			●				
Inundation and flooding	●	●	●	●	●	●	●	●	●	●	●	●	●
Inflow of detritus and polluted water					●					●	●		
Seepage and adsorption into landfill materials and coal					●							●	
Decreased water intake capacity					●					●			
Danger of ship collisions	●	●				●				●			
Corrosion and concrete deterioration	●	●	●	●	●	●	●	●		●	●		●
Lack of strength of structures	●	●	●	●	●	●	●	●	●	●	●	●	●
Subsidence and up-lift	●	●	●	●	●	●	●	●	●	●	●	●	●
Increased water spillage	●		●	●		●	●	●	●	●	●	●	●
Damage to road beds	●	●				●		●		●			
Reduced cargo handling capacity					●							●	●
Damage to cable-piping equipment	●	●	●	●	●		●	●		●	●		●
Damaged landscape			●						●				
Loss of water purifying function										●	●		

Note: This figure was made based on the Ports and Harbors Bureau, the Ministry of Transport (1991)

TABLE 7. IMPACTS ON TOKYO'S COASTAL FACILITIES

1st classification	2nd classification	3rd classification	Current Figure	Degree of Impact	Brief Assessment
Port facilities	Harbor facilities	Channels, anchorage and basin	6,080 ha	B	Reduced calmness
	Protective facilities	Breakwater	7,252 m	B	Increased wave overtopping
		Revetment	121,234 m	A	Loss of height to storm surge
	Mooring facilities	Quay wall, wharf	169 warfs	A	Possible inundation due to storm surge
		Inclined warf	3,695 m	A	Possible inundation due to storm surge
		Dolphin	57 (28 berths)	A	Possible inundation due to storm surge
		Floating pier	879 m	B	Change in bridge slope
		Mooring buoy	5 (5) buoys	B	Possible submergence
	Freight-handling facilities	Freight handling yard	125.6 ha	A	Possible inundation due to storm surge
		Shed	296,136 m^2	A	Possible inundation due to storm surge
		Cargo-handling equipment (Crane)	Many (24)	A	Possible inundation due to storm surge
	Storage facilities	Warehouse	1,081,761 m^2	A	Possible inundation due to storm surge
		Timber basin	192.2 ha	B	Loss of height
		Cool yard	4.7 ha	A	Possible inundation due to storm surge
		Oil storage facilities	Many	B	Possible inundation due to storm surge
	Passenter terminal facs.	Port traffic facilities	4	B	Loss of height
	Port traffic facilities	Road	Many	B	Possible inundation
		Railway	Many	B	Possible inundation
		Bridge	107 bridges	A	Insufficient clearance below bridges
		Submerged tunnel	2 tunnels	A	Increased water pressure, possible inundation
		Heliport	12.8 ha	B	Possible inundation due to storm surge
	Others	Park	19.8 ha	A	Possible inundation due to storm surge
		Artificial beach	about 3 km	A	Inundation, erosion
Protection facilities		Enbankment	30,676 m	A	Loss of height to storm surge
		Seawall	19,050 m	A	Loss of height to storm surge
		Groin	Non		
		Detached breakwater, wave-absorbing dike	Non		
		Gate	19 gates	A	Loss of height
		Pumping station	4 stations	A	Loss of height
River facilities		Enbankment	Many	A	Loss of height to storm surge
		Revetment	Many	B	Loss of height to storm surge
		Weir, gate	Many	A	Insufficient drainage capacity
		Sluice gate, pipe	Many	A	Insufficient drainage capacity
		Bridge	Many	B	Hindrance to ship navigation

A: Large B: Intermediate or possible C: Little

TABLE 8. IMPACTS ON TOKYO'S TRANSPORTATION AND ENERGY TRANSFER FACILITIES

1st classification	2nd classification	3rd classification	Current Figure	Degree of Impact	Brief Assessment
Road	Bridge		Many	A	Hindrance to ship navigation; Bridge piers must be reinforced.
	Tunnel		Many	B	Adequacy of physical strength must be investigated.
	Drainage		Many	A	Capacity must be expended.
Airport	Airport facilities			C	
	Runway		Three runways at Haneda Airport	C	
	Approach guidance light			B	Impact must be studied.
	Drainage			A	Capacity must be expanded.
Railway	Bridge		Many	A	Hinderance to ship navigation; Bridge piers must be reinforced.
	Tunnel		Many	B	Adequacy of physical strength must be investigated.
	Drainage		Many	A	Capacity must be expanded.
Subway	Bridge		Many	A	Hinderance of ship navigation; Bridge piers must be reinforced.
	Tunnel		Many	B	Adequacy of physical strength must be investigated.
	Drainage		Many	A	Capacity must be expanded.
Electric power plant	Cooling water discharge		13 power stations in Tokyo Bay	A	Impact of storm surge must be studied; a discharge facility is necessary.
	Drainage		13 power stations in Tokyo Bay	A	Facility must be expanded.
	Pier		13 power stations in Tokyo Bay	B	Impact must be studied.
Storage base	Oil tank		Storage is zero		
	LPG tank		940,000 tons	C	
	LNG tank		880,000 tons	C	
Electric power and city gas supply facilities, and telecommunication facilities	Multi-service tunnel		Many	B	Adequacy of physical strength must be studied.
	High-pressure natural gas piping		Many	B	Strength of valve station piping must be studied.
	Power line tower		Many	B	Corrosion resistance must be improved.

A: Large B: Intermediate or possible C: Little

TABLE 9. IMPACTS ON TOKYO'S FACILITIES RELATED TO DAILY LIFE

1st classification	2nd classification	3rd classification	Current Figure	Degree of Impact	Brief Assessment
Building	Plant, Warehouse	Wards	3,038.8 ha	B	Possible inundation
		Cities	1,073.1 ha		
		Towns and Villages	125.3 ha		
	Home Apartment	Wards	22,323.8 ha	A	Possible inundation, damage to daily life
		Cities	7,971.2 ha		
		Towns and Villages	323.4 ha		
	Office, Shop	Wards	6,414.2 ha	A	
		Cities	1,094.9 ha		
		Towns and Villages	33.1 ha		
Sewage	Pipe facilities	23 Wards	13,542.35 km	B	Lack of drainage capacity dur. heavy rain
		Tama area	160.30 km		
	Pump facilities	23 Wards; 67 pump facilities	38.26 ha	B	
		Tama area			
	Treatment facilities	23 Wards; 10 treatment facilities	281.98 ha	B	
		Tama area; 7 treatment facilities	125.56 ha		
Recreational facilities	Beach park	6 parks (including water zones)	618.5 ha	A	Decrease in flooding during storm surge
Waterworks	Water intake facilities	Tokyo Metropolitan Waterworks Bureau; 4 reservoirs		C	
		Under the control of the Water Resources Development Public Corporation; 4 dams			
		Under the control of the Ministry of Construction; 1 reservoir			
	Waterway	Under the control of the Tokyo Metropolitan Waterworks Bureau: 24 waterways	99,397.65 m	B	Detailed study is needed
		Under the control of the Water Resources Development Public Corporation; 2 waterways	16,050.29 m		
		Under the control of Ministry of Construction; 1 waterway	1,020 m		
	Water purification facilities	23 wards; 12 facilities Tama area; 59 facilities	159.20 ha	A	Lack of treatment ability
	Water transmission facilities	23 Wards; 11 lines	123,074.07 m	B	Possible corrosion
		Tama area	195,952.90 m		
	Water distribution facilities	23 Wards;		A	Possible corrosion
		23 Water supply places	51.18 ha		
		Waterworks piping	14,498.17 km		
		Tama area; 69 Water supply places			
		Waterworks piping	6,385.65 km		
Waste treatment facilities	Planned land reclamation (unfinished as of January 8, 1992)	Fiscal 1991; 4 places	4.07 ha	A	Outflow of waste, Lack of strength
		Fiscal 1992; 6 places	351.82 ha		
		Fiscal 1993; 5 places	43.89 ha		
		Fiscal 1994; 5 places	27.79 ha		
		Fiscal 1995; 4 places	20.15 ha		
		Fiscal 1996; 2 places	356.34 ha		

A: Large B: Intermediate or possible C: Little

IMPACTS ON THE COASTAL ZONE FACILITIES

TOKYO PORT AND HARBOR

Tokyo Port has 169 berths of quays, 28 berths of dolphins, and other facilities. This port currently handles 25 million tons of export-import cargo and 54 million tons of domestic cargo.

Since most of the mooring facilities in the port have been at the level of low water plus 4 meters (i.e., high-water level +2 meters), a 1-meter rise in sea level would not cause flooding at normal conditions. However, since sea level rise would be accompanied by higher waves, the following effects could be anticipated.

- Decrease in the calmness of the harbor basin due to increased wave height and wave overtopping. Adverse effects related to this.
- Inundation of wharves during storm surges.
- Loss of safety for quays and breakwaters due to increased wave forces.
- Changes in wharf heights relative to ship deck height. Increased slope of gangways. Hindrance of ship navigation due to decreased clearance below bridges.
- Submergence and changes in positions of fenders.

A 2- to 3-meter storm surge must be considered to assess impacts on Tokyo's port. Since many facilities are outside high-tide embankments and are not protected, they would most likely be damaged once the storm surge occurred. If the sea level rises, the storm surge would have a much greater impact. If a 2-meter storm surge took place at flood tide, some quays would end up 1 meter under water. Moreover, wave action would most likely seriously damage buildings and other mooring facilities.

RIVERS

Both large rivers and medium to small rivers in Tokyo have very small surface gradients and are tidal rivers. Increases in the sea level at the river mouth would inevitably decrease the capacity of flood discharge. When the storm surge and wave runup (0.5–2.9 meters) are taken into account in addition to sea level rise, the present height of the embankments may be quite inadequate. However, since the height of the embankments according to the current plan was designed for a 3-meter storm surge, it is necessary to take this allowance into account, as well as the effects of increased typhoons and rainfall. Other possible effects on the rivers are as follows:

- Lack of adequate capacity for water discharge and drainage in lowlands during storm surges.
- Lack of capacity for ordinary discharge and deterioration of water quality.
- Inundation of high-water channel.
- Salinity intrusion into rivers.

- Hindrance to ship navigation due to insufficient clearance below the bridges.

- Decrease in functions of structures.

IMPACTS ON OTHER FACILITIES

The serious effects on other facilities include the following:

- Roads and railways may be flooded. There will be extra water pressure and buoyancy for the tunnels.

- The airport may be flooded during the storm surge.

- Since power and city gas production and storage facilities are mostly located on the waterfronts in the Tokyo metropolitan district, they face the same risk as do ports and harbors. Line facilities, including those for telecommunications, may also be flooded.

- Many buildings on the lowlands are so low they would sustain great flood damage.

- The sewage system in the lowlands may not be able to drain all the rainwater or wastewater, and a reverse flow may result.

- Due to the inflow of sea water, some of the waterworks may not be able to collect water, causing water quality to deteriorate and increasing water treatment expenses.

- An effect common to many different facilities will be the danger of liquefaction caused by the increased ground-water table.

Sea level rise will exacerbate the damage caused by typhoons and earthquakes. There will be direct danger from flooding of waterfronts and the lowlands, while other areas will face indirect dangers, such as the disruption of transportation, energy supplies, and telecommunications.

IMPACTS ON ECOSYSTEMS, AGRICULTURE, AND FISHERIES

In Japan, many embankments and other protective facilities have been built on coastlines. Consequently, there is not much room left for the natural geographical features and ecosystems to retreat inland. Therefore, the impact of sea level rise on natural beaches would be great. However, little is known on this subject, though efforts have been made to assess the effect of global warming on marine resources and fisheries (e.g., Ministry of Agriculture, Forestry, and Fisheries, 1989).

RESPONSE OPTIONS

CURRENT PROTECTION STRATEGIES

Japan has protected its coast in accordance with the provisions of the Coast Law enacted in 1956. Approximately, 0.04–0.05 percent of the Japanese GNP has been allotted for this work, with the figure in 1988 standing at 0.045 percent.

In addition to the government-executed work, the national government subsidizes the following: high-tide countermeasures to protect national land from storm surges and *tsunamis*, erosion countermeasures to protect national land from erosion, coastal environment improvement to create comfortable beaches, and other works. The main percentage figures are 44 percent for high-tide countermeasures, and 24 percent and 20 percent for the erosion countermeasures and coastal environment improvement, respectively.

In Japan, the following countermeasures centered on building structures have been protecting inland areas.

- High-tide (storm surge) countermeasures

    a. Embankments, sea walls.
    b. Detached breakwaters, submerged breakwaters, wave-absorbing dikes, artificial reefs.
    c. *Tsunami* breakwater.
    d. Combination of a, b, and c.
    e. Others.

- Erosion countermeasures

    a. Detached breakwaters, submerged disks, jetties, artificial reefs, artificial headlands.
    b. Artificial beach nourishment (including sand bypassing).
    c. Combination of a and b.
    d. Others.

To protect cities that are located on lowlands near river mouths, high-tide embankments with high crown heights have been built around coastlines and river banks. Combined with watergates and the pumping stations, they keep the inside water level low. This combined method reduces the required length of high-tide embankments, and is thus economical.

With this historical background, the basic protection measures Japan must take against sea level rise must involve "hard" structures.

RECOMMENDED RESPONSE STRATEGIES

The IPCC CZMS has conducted studies on response strategies against sea level rise to be taken in coastal zones throughout the world. In its first report, the CZMS proposed three basic strategies: retreat, accommodate, and protect.

Japan does not have much room for flexibility in considering various protection options. Since the expanded flood-prone area that would be created by a 1-meter rise would involve 15 million people and assets worth ¥380 trillion, it is obvious that we would need to protect these areas very firmly. The basic measures of protection would be to reinforce disaster-prevention systems, such as raising the ground, embankments and sea walls, and reinforcing the drainage pumps.

Up until now, there has been no comprehensive cost estimate on raising the structure for all of Japan. However, the Ministry of Construction estimated a cost of ¥6 trillion (U.S. $6 billion) for a 3.5-meter increase in embankment height along 2,700 km of coastline under its jurisdiction. The Ministry of Transport also estimated a cost of ¥1.5 trillion (U.S. $12 billion) to raise embankments by 1.1 meters along about 3,000 km of coastline under its jurisdiction. Moreover, a cost of about ¥2.3 trillion (U.S. $18 billion) was estimated for raising harbor facilities by 1.1 meters. All in all, about ¥10 trillion (U.S. $77 billion) would be necessary only to maintain the current protective structures and ports and harbor facilities.

No estimate is available for the required number of additional pumping stations and the additional amount of drainage on a nationwide basis. Moreover, there has been no estimate on the cost of extensive land reclamation, because land availability and the costs of sand and earth vary widely, depending on the particular locality and on future economic trends. For the strategy of protection, estimates should be made not only for raising structures, but also for comprehensive measures to be taken in the future.

Land reclamation and waterfront development continue mainly around large cities. It may not be sufficiently safe to rely on the existing measures for protecting infrastructures and city areas. Instead, countermeasures against future climate changes must be incorporated, in advance, into the design standards for new facilities. Efforts must be paid further to build a city that can withstand disasters coming from the sea. This effort should include strengthening the disaster-prevention facilities of waterfronts and lowland areas, dispersing highly concentrated functions to safer areas, and paying serious attention to sea level rise in order to improve standards for waterfront development and city planning.

Moreover, if we should continue to use structures alone for protection, the entire Japanese coast will soon be surrounded by protective structures. The remaining natural sea coasts, however, are precious resources, and their preservation is an important subject for Japan. Many different options must be examined, including a retreat inland from the endangered coastlines.

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RÍO LAGARTOS, YUCATÁN, MEXICO, SPECIAL BIOSPHERE RESERVE: A CASE STUDY

Gustavo de la Cruz Agüero and Gerardo Gold Bouchot
Cinvestav-IPN, Unidad Mérida
Yucatán, México

Víctor Alcántar Cárdenas and Juan José Durán Nájera
SEDUE Delegación,
Yucatán, México

INTRODUCTION

Río Lagartos Biosphere Reserve covers and area of 47,840 ha. The only nesting place in North America for the Caribbean Flamingo (*Phoenicopterus ruber*), Río Lagartos was designated a wildlife refuge in June 1979 by the Mexican government. In 1988, after the Mexican Congress enacted the General Law of Ecological Equilibrium and Environmental Protection, Río Lagartos was declared a Special Biosphere Reserve. Since 1986, the Mexican government has committed itself to protect this area by subscribing to the RAMSAR Wetland Convention. Río Lagartos is the only place in Mexico on the List of Wetlands of International Importance.

This study was conducted to determine the ecological and socioeconomic impacts of accelerated sea level rise on the reserve and appropriate responses to mitigate those impacts. The results presented here are preliminary.

THE STUDY AREA

GEOLOGIC CHARACTERISTICS

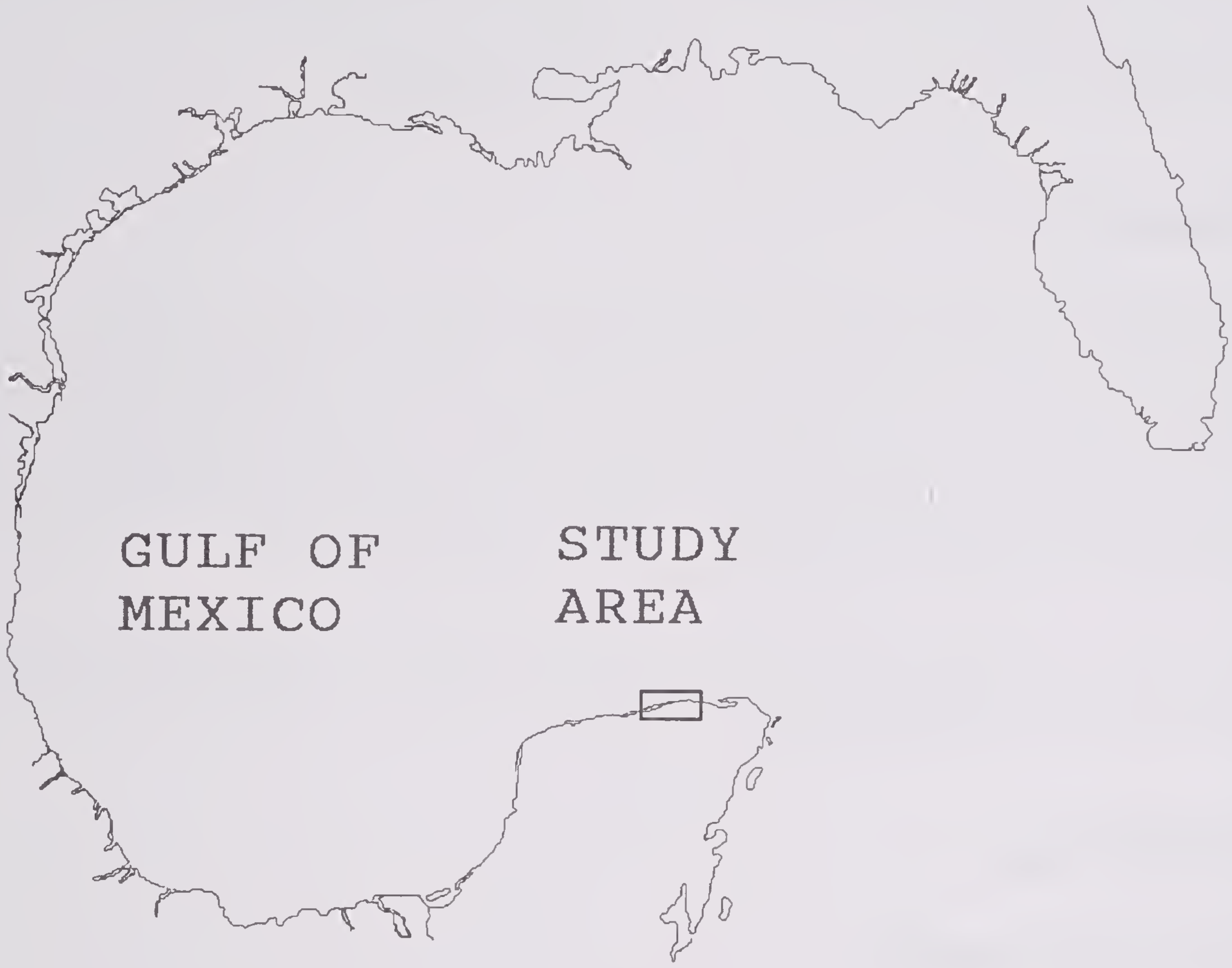
The Yucatán Peninsula is formed by a calcareous plain, composed of tertiary limestone. The lack of clay from the upper tertiary above the limestone makes it highly permeable. Rainfall infiltrates fast, dissolving the rock and producing a karstic relief. The eastern portion of the peninsula, where the reserve is located, is characterized by a rough white or light gray calcareous shield that frequently outcrops forming rocky soils. However, probably because the reserve is located in the humid region of the state, the carbonates have dissolved and have created many sink holes, forming a complex web of caves, cenotes, etc., with or without communication with the outside (Duch 1988).

Between the coastal dune and the karstic plain, the Yucatecan aquifer is confined by a layer of evaporitic calcite. Locally known as *caliche*, this calcite cements the pores and cracks in the limestone, precisely in the continental discharge zone of the aquifer to the coast, forming swamps, coastal lagoons, and wetlands. This thin layer (0.5 to 1.4 meters) extends along the 350 km of coastline in the state of Yucatán, with a width of 2 to 20 meters (Figure 1).

This coastal *caliche* is practically impermeable. With a porosity of less than 1 percent, it acts as a barrier to the underground flow of ground water to the sea. This has two consequences: (1) at a distance of 5 to 7 km inland from the coast, the aquifer has a hydrostatic head of 0.32 to 0.77

meters above mean sea level, in accordance with the change of the tides, being significantly higher than the level of surface waters during the rainy season; and (2) in the sea, the *caliche* (which can extend for more than 3 km) is destroyed by biological processes (Perry et al., 1989).

FIGURE 1. THE RÍO LAGARTOS STUDY AREA



On the other hand, behind the coastal dune the mean water level is below the mean sea level, in spite of the freshwater flow from springs and marshes. This is because of the high evaporation rate (Perry et al., 1989).

In Yucatán there is a single aquifer that is karstic, very permeable, and hydrologically heterogeneous. It has a mean depth of 150 meters, limited below by low-permeability clays. Saltwater intrusion has been detected 100 km from the coast (SARH 1988). Because of this intrusion, the depth of fresh water increases inland, being less than 30 meters 20 km inland, between 30 and 100 meters in the plain and 100 meters in the hills.

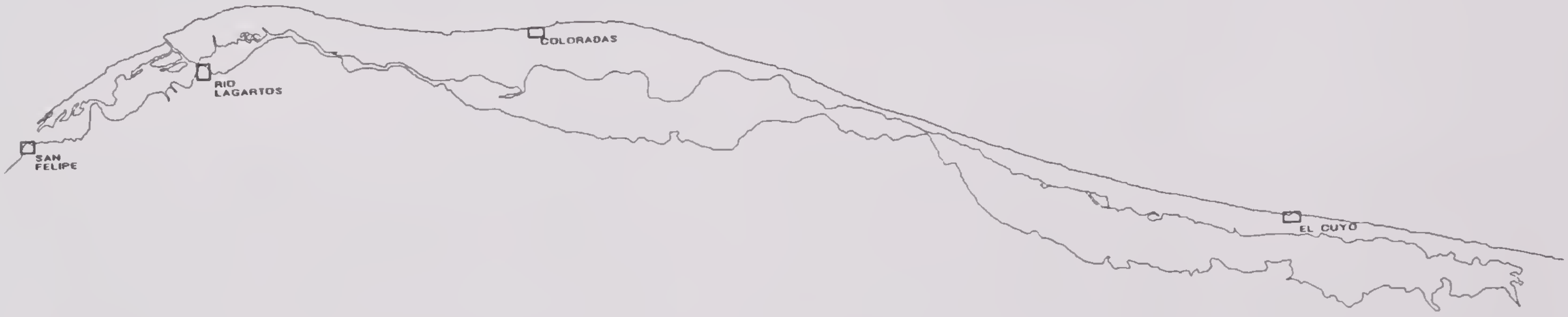
Under the extreme conditions created by hurricane *Gilbert*, there was a storm surge of 7 meters, which flooded approximately 5 km inland. This phenomenon significantly modified the aquifer at distances of up to 25 km from the coast, mainly in the northwest region of the peninsula, where one day after the storm the depth of the aquifer increased by 0.64 to 1.1 meters (Villasuso et al., 1989).

Río Lagartos consists of several different environments around a hyperhaline lagoon. Separated from the sea by a sandy barrier, this kind of lagoon is known locally as a *ria*. The lagoon is approximately 70 km long, with a surface area of 9.37 km^2 (Figure 2). Its northern side is formed by a classic barrier island, the product of sediment deposition provoked by the action of waves and the marine current. The southern side and the bottom are formed by the margin of the peninsula, which is a limestone modified by karstic processes. There is no surface runoff of fresh water, but there is a strong flow of ground water through the aquifer, and some springs on the bottom of the lagoon. The water runs to the sea through the natural opening at San Felipe, and through the artificial opening at Río Lagartos. The lagoon is very shallow, with a mean depth of 1 to 1.5 meters. Because of its restricted interaction with the open sea, it has a long water residence time. Also, because evaporation is higher than precipitation, waters to the east are increasingly saline. Thus, in El Cuyo basin, salinity can be as high as 180 parts per thousand (unpublished data).

Due to its geographic location on the northern shore of the Yucatán Peninsula, Río Lagartos has only two climate seasons: the rainy season from June to November, and the dry season from December to May. Also, strong northern winds known locally as *nortes* prevail from November to April. They increase the flow of salt water into the lagoon, which raises oxygen levels and lowers the temperature. Hurricane season is from August to October.

According to the topographic maps (1:50,000) from the Instituto Nacional de Geografíca, Estadística e Informática, the terrain in the reserve has elevations of +2 meters in Río Lagartos to -3 meters at El Cuyo, with respect to mean sea level. This favors the leakage of water from both the aquifer and the sea to the lagoon, pushed by a hydrostatic head of 3 meters. The system of coastal dunes also has an important aquifer, floating as a lens on the salt water, with favorable conditions for the existence of rainforest plant species, such as the *zapote* (*Manilkara zapota*) (Espejel, 1984).

FIGURE 2. HYPERALINE LAGOON OF RÍO LAGARTOS



BIOLOGICAL DIVERSITY

Mexico is highly diverse biologically. It is considered to have the world's greatest diversity of reptiles, with 717 recorded species. It also ranks second in the category of mammals, with 449 species, and fourth in amphibians, with 282 species (see Table 1). For plants, it is estimated that there are 283 endemic genera, representing 64 families, and a total of 2,780 endemic plants (Conservation International 1990; Cloud and Toledo 1989). For the state of Yucatán, there are 2,100 plant species recorded, 17 percent of which are endemic (Souza et al. 1980; Toledo 1985). For instance, the tropical deciduous forest in the Yucatán Peninsula is considered very important for its high degree of endemic species (Rzedowski 1978). There are 11 endangered plants species in the state (Flores and Gerez 1988). Yucatán holds 19th place in vertebrate diversity in Mexico. There are 142 species of terrestrial vertebrates endemic to Mesoamerica, 15 of which are endemic to Mexico and only one to the state.

TABLE 1. BIODIVERSITY OF STUDY AREA

		RÍO LAGARTOS SPECIAL BIOSPHERE RESERVE		
TAXA	MEXICO	Total	Endangered	Spp/km^2
Plants	4-5 x10^3	2,100	4?	7.1
Fish	?	70	--	7.4
Amphibians	282	?	--	
Reptiles	717	?	4	
Birds	800?	260	18	5.4
Mammals	449	?	8	

The Río Lagartos reserve is one of the most important wetlands in the Yucatán Peninsula. It comprises a great diversity of habitats: mangrove swamps and forests; tule swamps; coastal dunes; sink holes; wet low forest; low deciduous forest with cacti; and, in the hyperhaline lagoon, a highly productive stromatolith formed by an association of algae and bacteria, and sea grass beds (see Table 2).

TABLE 2. NATURAL SYSTEMS COVERAGE

Habitat	**km2**
Mangrove	7.30
Sea Grass	3.01
Stromatolith	3.13
Sand Dunes	3.00
Tule Swamp	5.50
Wet Low Forest	2.80
Deciduous Forest	0.35
Subdeciduous Forest	1.00
Peten	0.30
Total	**47.84**

In this reserve, more than 260 species of birds have been recorded, of which 58 percent are resident and 38 percent are migratory (García and Correa, 1989). The lagoon is the only nesting place of the Caribbean Flamingo (*Phoenicopterus ruber*) in North America. The reserve is also a refuge for important migratory birds, such as the white pelican (*Pelecanus erythrorhynchos*), and winter grounds for shore birds from the families Lariidae, Charadriidae, and Scolopacidae. Some, like the jabiru stork (*Jabiru mycteria*) and the peregrine falcon (*Falco peregrinus*), are seasonal visitors. In the southern part of the reserve, in the low forest, there are ocellate turkeys (*Agriocharis ocellata*), which is an endemic and endangered species.

The reserve's beaches are considered the most important nesting places for the hawksbill turtle (*Eretmochelys imbricata*) and the green turtle (*Chelonia midas*), both considered to be endangered species. The presence of crocodiles (*Crocodylus acutus*) has been reported. There are 22 recorded species of mammals, including several felines, such the as jaguar (*Felis onca*) and the jaguarundi (*Felis yagoarundi*).

Two endangered species of palm are among the most important plant species in the reserve: *kuka* (*Pseudophoenix sargentii*) and *chi'it* (*Coccothrinax readii*). There are also some endemic groups of Cactaceae, such as *Mamillaria gaumieri* and *Cephalocereus gaumeri*.

In the aquatic environment are underwater plant communities, especially where the water is transparent. The main species in those communities are green macroalgae, changing in structure and distribution following the salinity gradient. Of the total number of fish species (more than 70), more than half use this system as refuge, feeding, or growing zone. Some of the plants have commercial value, inside the lagoon and/or when they are back to the sea.

SOCIOECONOMIC ASPECTS

There are four human settlements inside the reserve. Table 3 shows the total population distribution for the four human settlements in the reserve (Fraga, 1991):

TABLE 3. POPULATION DISTRIBUTION

Village	Inhabitants	Houses
San Felipe	1,434	306
Rio Lagartos	1,619	270
Coloradas	779	144
El Cuyo	793	140
Total	**4,625**	**860**

The houses are small buildings, some of them constructed of local materials (palm leaves for the roof and walls, tree trunks for the building frame, etc.).

The main economic activities along the northeastern coast of the peninsula are fishing in San Felipe, Río Lagartos, and El Cuyo; and salt mining in Coloradas. In 1988 the fisheries production was 3,952 metric tons in 1988 (SEPESCA, 1989). On the other hand, salt production before hurricane *Gilbert* was reported to be 500,000 metric tons/year. Other economic activities include coconut plantations, agriculture, cattle raising, and tourism (on a minor scale). Table 4 breaks down the distribution of land ownership in the reserve. Table 5 illustrates the fishing infrastructure in each village (SEPESCA, 1989):

TABLE 4. DISTRIBUTION OF LAND OWNERSHIP

Land Use/Ownership	km^2
National	16.84
Private	7.51
Salt Mining	9.07
Fed. Maritime Zone	1.40
Communal	0.34
Agriculture	0.53
Cattle	0.39
Urban	0.11

TABLE 5. VILLAGE FISHING INFRASTRUCTURE

Village	Breakwater (meters)	Pier (meters)	Sea Wall (meters)
San Felipe	461	60	1,000
Rio Lagartos	556	25	2,000
Coloradas	---	100	-----
El Cuyo	598	---	-----

Other important infrastructure are an ice factory in San Felipe, a gas station and ice factory in Río Lagartos, and a gas station and ice factory in El Cuyo.

IMPACTS AND RECOMMENDED RESPONSES

Table 6 presents the expected impacts resulting from a 3-meter and a 1-meter rise in sea level.

TABLE 6. GROSS IMPACT ASSESSMENT FOR SEA LEVEL RISE

Type	**Sea Level Rise**	**Sea Level Rise**
	0.3 meters	*1.0 meter*
Sandy Shore	1.98 km^2	6.6 km^2
Lagoon Fringe	0.63 km^2	2.1 km^2

The potential impacts from sea level rise in the reserve were divided into three categories: (1) impacts on the middle part of the narrow sand barrier that separates the hyperhaline lagoon from the sea; (2) impacts on the natural habitats in the reserve; and (3) impacts on the human settlements and economic activities. Table 7 presents the recommended responses for these impacts.

TABLE 7. POTENTIAL RESPONSE ACTION TO SEA LEVEL RISE

Category of Impact	**Action**	**Cost (U.S. $)**
Sand Barrier	Protect	$5 million
Natural Habitats	?	---
Socioeconomic Activities	Protect	$500,000
Salt Mining	Adapt	?

SAND BARRIER

This area is 15 km long. Because it was seriously weakened by the Hurricane *Gilbert*, it should be the first affected site. Actually, due to occasionally stronger northern winds, the sea water invades the lagoon, reducing its salinity. The most effective protection for this area would be to construct a sea wall along the 15 km. This would cost $5 million (U.S.), and does not include the cost of additional restoration actions to promote the dune plants' regeneration.

NATURAL HABITATS

The reserve's several different habitats have been well preserved. To date we do not know what kind of actions could be taken to protect or to mitigate the impacts on the natural habitats. It is expected that a gradual rise in sea level could produce adaptive responses within the natural communities.

SOCIOECONOMIC ACTIVITIES

Almost all the villages are 1–3 meters above sea level, above the expected risk limit. San Felipe and Río Lagartos are 1 meter above sea level, but they actually have sea walls. Fisheries are not expected to be affected. On the other hand, the salt industry actually has pond walls 2 meters above the sea level; however, the salt productivity would lower with sea level rise because of the dilution of the hyperhaline waters by the intruding sea water (see Table 7).

To protect these activities against sea level rise, the sea walls around San Felipe and Río Lagartos should be reinforced. This would cost an estimated U.S. $500,000 for both villages. In addition, the salt industry needs to reinforce its pond walls. We have not estimated the cost of this action.

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Efectos del Incremento del Nivel del Mar en la Costa Peruana por Influencia del Calentamiento Global (1era. Etapa)

Impacts of Sea Level Rise on the Peruvian Coast
Caused by Global Warming (First Stage)

César del Carmen de la Torre and Gustavo Laos C.
Dirección de Hidrografía y Navegación
Callao, Perú

Abstract

This work consists of the collection and analysis of existing information within Peru and abroad. Some of the data analyzed include sea levels, tidal characteristics, coastal types, waves (direction, height, and period), "Bravezas del mar," coastal slopes, infrastructure, and population.

This study considers a 1-meter scenario of sea level rise by delineating areas that are currently flooded during high tides and storm surges coinciding with "Bravezas del mar." Estimates are made for height and directions of waves, taking into account coastal morphology and slopes to determine zones of maximum flooding.

The following ports were studied: Paita, Salaverry, Chimbote, Callao, Pisco, San Juan, Matarani e Ilo. These ports were selected because they are strategic for the socioeconomic development of the country, and their population depends directly on coastal activities.

It was concluded in this first study phase that the ports of Pisco and Ilo, the cities of Chucuito and La Punta in the Callao area could be severely affected. In general, part of the coastal population and infrastructure could suffer some of the impacts of sea level rise. Docks could be affected because they were designed for other conditions and they could be in danger of collapsing.

Summary of the Study

1. The present preliminary study, in its first phase, had a cost of U.S. $1,000, not including salaries for specialists. It is estimated that a pilot project of the port of Pisco, as recommended by this first phase, could cost up to U.S. $10,000. An extended study of the entire Peruvian coast could cost approximately U.S. $200,000.

2. Statistical data on sea level, waves, "Bravezas," and some figures for slopes where readily available from this institution (Dirección de Hidrografía y Navegación), which manages these data.

One of the limitations of readily available data included the lack of maps with small scales that show contours of 1, 5, and 10 meters where to delineate the maximum flooding zone and, therefore, account for the infrastructure at risk. Also, up-to-date census information on the Peruvian population is lacking, even though the government has scheduled a census for 1993.

Another limitation that this study found was the lack of specific information on existing infrastructure available in a single government entity, such as municipalities. Finding this information could require an extensive search throughout the government agencies.

3. This study identified three localities, at a reconnaissance level, that could be affected along the Peruvian coast for a possible 1-meter sea level rise in the next 100 years: Chucuito and La Punta, Pisco, and Ilo.

   Specifically, for the areas of Chuchito and La Punta, it was estimated that if no action is taken, La Punta could be transformed into an island as sea level rise could breach the area from the continent around Chuchito. The inhabitants of La Punta could suffer more frequent flooding problems during the events of "Bravezas de mar."

   A similar problem could occur in the area of Pisco, especially the city of San Andres.

4. Potential problems associated with sea level rise impacts could be solved by the construction of sea walls and breakwaters along the coast of Chucuito and La Punta. This is justifiable because of the importance of this coastal zone from tourism, population, and commercial points of view. In the case of San Andres, in Pisco, relocation of its population could be the most efficient response.

5. There is a national consensus among the Peruvian institutions of the importance to perform a study on the entire arrays of possible climate changes. National authorities are becoming more aware of potential problems of climate change. A group chaired by a representative of the Ministry of Foreign Affairs was formed in July 1991 to complete studies in different areas and to recommend actions to the government on planning, environmental protection, and future development.

6. We believe that we are starting to take action. The first step is to estimate how and how much Peru could be affected by the projected different scenarios of climate change.

RESÚMEN

El trabajo consiste en la agrupación y análisis de la información existente en nuestro medio y en el extranjero, los datos que se analizan, en general, son los siguientes: nivel del mar, características de las mareas, tipos de costa, oleaje (dirección , altura y período), bravezas de mar, pendientes de costa e inventario de la infraestructura y su población.

Se considera un incremento del nivel del mar de 1 metro, delimitando las áreas inundadas en períodos en los que las más altas mareas observadas y la pleamar superior coinciden con épocas de Bravezas de mar. Se hacen cálculos de alturas y dirección del oleaje en costa, considerando la morfología de la costa y pendiente, para calcular las zonas de máxima inundación.

Los puertos estudiados son Paita, Salaverry, Chimbote, Callao, Pisco, San Juan, Matarani e Ilo, por considerarlos puertos estratégicos en el desarrollo socio-económico en donde se concentra la población comercial y una población dependiente de dicha actividad.

En esta primera etapa del trabajo se concluye que los puertos de Pisco e Ilo y la ciudad de Chucuito y La Punta en el Callao podrían verse fuertemente afectados. En general, parte de la población e infraestructura costera si sufrirían los efectos del incremento del nivel del mar. Los muelles se verían afectados ya que cambiarían los objetivos para los cuales fueron construidos y estaría en peligro de colapso su infraestructura.

INFORME RESÚMEN

1. El estudio preliminar, en su primera etapa, representó un costo aproximado de 1,000 dólares americanos, sin incluir los honorarios de los especialistas.

   Se estima un costo total para el estudio piloto en el puerto de Pisco, de acuerdo a la recomendación del informe, de 10,000 dólares americanos y que al hacerlo extensivo a toda la costa podría significar un costo aproximado de 200,000 dólares americanos.

2. No representó un problema obtener los datos estadísticos de niveles de Mar, Olas y Bravezas, incluyendo algunos datos de pendiente de costa, ya que la misma institución (Dirección de Hidrografía y Navegación) maneja esa información.

   Una de las limitaciones fué la obtención de cartas a una escala tal que pueda observarse claramente las cotas de 1, 5 y 10 metros, para poder delimitar la zona de máxima inundación y de esta manera inventariar la infraestructura que se encuentra dentro de dicha área.

   No existe un censo actualizado de las poblaciones en el territorio peruano, pero el gobierno ha programado uno para realizarlo durante el año 1993.

   Otra limitación encontrada fué la de inventariar en forma más específica las infraestructuras existentes, ya que muchas de sus características no se encuentran en un sólo lugar, como pudiera ser las Municipalidades, entonces habría quizás que tocar de puerta en puerta para conocerlas mejor.

3. Se han identificado, en un principio, zonas de impacto en la costa peruana, principalmente en tres localidades, si es que hubiera un incremento del nivel del mar de 1 metro para los próximos 100 años,: Chucuito y La Punta, Pisco e Ilo.

   Específicamente para Chucuito y La Punta, se estima que si no se toman medidas, La Punta podría convertirse en una isla al separarse, por efecto del incremento, del continente por la zona de Chucuito. Además la población que actualmente vive en La Punta, en épocas de Bravezas de mar, sufrirían constantemente problemas de inundación.

   Pisco, específicamente la ciudad de San Andrés, se encontraría constantemente con problemas de inundaciones en épocas de Bravezas de mar.

4. Se cree que para resolver el problema de Chucuito y La Punta la construcción de muros de contención y rompeolas ayudaría, y en principio justificaría su protección,

ya que es una zona bastante estratégica, bajo el punto de vista turístico, poblacional, y comercial.

Se piensa que una reubicación de la población de la ciudad de San Andrés en Pisco sería lo más conveniente.

5. Actualmente existe un consenso institucional sobre la importancia de efectuar estudios completos con respecto a los cambios climáticos.

   Las autoridades están tomando conciencia ante estos problemas; en tal sentido, en el Perú, existe un grupo de trabajo presidido por un representante del Ministerio de Relaciones Exteriores, que se viene reuniendo desde Julio de 1991, para poder efectuar estudios conjuntos, en los diferentes campos, y recomendar acciones al gobierno en cuanto a la planificación, la protección del medio ambiente y los intereses de desarrollo.

6. Las acciones, creo que las estamos empezando a tomar, lo primero es efectuar los estudios para ver cómo y cuánto nos puede afectar los cambios climáticos de acuerdo a los escenarios propuestos.

INTRODUCCIÓN

ANTECEDENTES

El aumento del nivel del mar a nivel global como consecuencia del calentamiento climático potencial es objeto de intensa atención en la actualidad. Los especialistas sugieren un incremento probable de medio metro durante el próximo siglo, aunque todavía existe incertidumbre en esta estimación.

Hoy en día, en la Comunidad Científica Internacional existe el concenso de que los cambios climáticos vienen originando cambios globales y que es necesario diseñar y poner en práctica planes de acción, para enfrentar en mejores condiciones sus efectos negativos en el futuro. El calentamiento de la atmósfera terrestre en particular y del planeta Tierra en general, es un hecho que debe ser reconocido y afrontado a la brevedad.

Si bien es cierto que las márgenes costeras son ambientes dinámicos, en constante proceso de cambio, y que una subida del nivel del mar va a depender, localmente, de muchos factores, se hace necesario hacer estimaciones cualitativas y cuantitativas de los efectos que podría causar una subida del nivel del mar en nuestras costas, ya que en éllas se han establecido puertos marîtimos, en donde se concentra la actividad socioeconómica y en consecuencia la mayoría de la población, constituyendo polos de desarrollo al permitir el comercio interior y exterior.

Como experiencia de trabajo en el Perú, la Dirección de Hidrografía y Navegación viene operando desde la década de los 40 la Red Nacional de Estaciones Mareográficas en los principales puertos de la costa y mar peruanos; por otro lado también tiene entre sus funciones el levantamiento hidrográfico de toda la costa, como resultado de lo cual se ha desarrollado la Cartografía Naútica, que incluye la Topografía de las zonas costeras.

OBJETIVOS

- Determinar en forma cuantitativa y cualitativa los efectos que causaría en las zonas costeras un incremento del nivel del mar de aproximadamente 1 metro, por encima de las más altas mareas, como resultado del calentamiento global.

- Delimitar las zonas de inundación causadas por Bravezas de Mar que se produzcan en pleamares máximas, como consecuencia del incremento de 1 metro sobre el nivel medio del mar.

- Establecer conceptos, difundir y obtener datos, lo más precisos posible, para ser empleados en el planeamiento de futuros asentamientos humanos a lo largo de la costa peruana.

CONSIDERACIONES PARA EL ESTUDIO

LA COSTA EN ESTUDIO

La detección de cambios a corto plazo en el nivel del mar requiere una instrumentación muy precisa. En la actualidad se utilizan aparatos de registro continuo de mareas (mareógrafos). Algunos puertos poseen una larga historia de mediciones del nivel de las mareas, pero a menudo existen dificultades al comparar los registros antiguos y modernos debido a los cambios en el tipo de medición utilizada. La comparación de datos de marea de muchos lugares esparcidos por todo el globo, parece indicar que durante la primera mitad de nuestro siglo hubo una pequeña elevación del nivel del mar del orden de 1 milímetro por año.

A través de los años el nivel del mar ha fluctuado considerablemente. Los profundos surcos submarinos y las grandes cordilleras del fondo del mar nos indican que los procesos tectónicos han levantado y hundido el lecho marino, actuando sobre zonas muy extensas, variando, por tanto, la capacidad de contenido de las cuencas océanicas. Además, durante el Pleistoceno, el nivel del mar cambió rápidamente como consecuencia de la formación y de la fusión de los glaciares continentales. Hay pruebas que indican que el nivel del mar descendió casi 140 metros a medida que los glaciares continentales se expandían durante el último período de la glaciación (Wisonsin, Wurm). Cuando los glaciares empezaron a fundirse, hace unos 15,000 y 18,000 años, el nivel del mar, empezó a subir. Hace unos 6,000 años alcanzó, aproximadamente, su nivel actual. Desde entonces han tenido lugar tan sólo cambios muy pequeños; el resultado final ha sido probablemente, un pequeño aumento en el nivel del mar.

Para complicar las cosas, también los márgenes continentales de los océanos han quedado sujetos a cambios de elevación. Los procesos tectónicos que actuaron en el Pleistoceno y que han venido operando hasta ahora, han levantado y hundido zonas del litoral a lo largo de muchas costas.

En el caso del Perú, la actual costa ha estado expuesta durante su larga historia geológica a levantamientos y hundimientos. En la zona Norte, que abarca desde la frontera con el Ecuador hasta Punta Aguja, las formaciones geológicas indican que allí la costa se ha elevado recientemente. Los grandes tablazos que se extienden desde Paita hasta Zorritos y que han traido a la superficie sedimentos terciarios y otros cuaternarios a niveles poco elevados sobre el nivel del mar así lo señalan. La superficie del desierto de Sechura, cubierta en grandes extenciones por una cantidad de moluscos marinos y la existencia de bancos de bivalvos incrustados en los ancantilados arenosos comprueban que la elevación de la costa sobre el mar se ha llevado a cabo en tiempos geológicamente recientes.

En la zona Centro, que comprende la costa situada entre Punta Aguja e Isla San Gallán, la configuración del litoral es otra. Cerca a la costa se levantan las Islas. En algunas de ellas se han descubierto rocas metamórficas, restos de la Cordillera de la Costa o de una de sus ramificaciones. En el período Mioceno empezó el hundimiento de partes pertenecientes entonces al continente, y con este hundimiento la destrucción paulatina de la Cordillera de la Costa.

En la zona Sur, que abarca desde la Isla San Gallán hasta la frontera con Chile, se distinguen dos sectores geológicos. Uno comprendido entre la Península Paracas y Caravelí, que está en levantamiento debido principalmente a la actividad tectónica que ocaciona que la Dorsal de Nazca, al subsidir sobre el continente Americano, produzca áreas de levantamiento; y la zona entre Caravelí y la frontera con Chile, que parece haber experimentado un hundimiento complicado por varias etapas con un resultado reciente de un levantamiento reducido.

Todas estas características de nuestras costas sumadas a los procesos de erosión, que se producen en mayor cuantía, entre la Península de Paracas y la frontera con Chile, en donde predominan los grandes acantilados; y los procesos de sedimentación, entre la Península de Paracas y la frontera con Ecuador, hacen que algunas áreas de nuestras costas se encuentren más vulnerables al incremento del nivel del mar, lo que amerita tenerlas muy en cuenta en un estudio detallado al respecto.

LAS BRAVEZAS DE MAR

Frente a nuestras costas y durante cualquier época del año, el comportamiento del oleaje presenta alteraciones en su amplitud respecto a las condiciones normales, a las cuales se denomina Bravezas de Mar. Las Bravezas de Mar que afectan a nuestras costas, son el resultado de profundas alteraciones atmosféricas, como tormentas que circulan sobre las latitudes altas, o el resultado de la intensificación del viento. Las Bravezas a lo largo de la costa peruana son generadas bajo la influencia del viento; su forma y altura van a depender entonces de la fuerza y persistencia del viento.

La zona en donde las tormentas se desarrollan frecuentemente, se sitúa más o menos entre las latitudes 35° S y 40° S, mientras que la longitud Oeste del centro de perturbación varía con mayor amplitud, es en esta área en donde se produce la mayor subsidencia atmosférica y consecuentemente divergencia del viento en superficie.

En promedio, la Braveza de mar se demora en llegar a las zonas costeras del Perú, después de su generación, entre 40 a 60 horas, y en algunos casos más de 80 horas.

El tiempo que dura una braveza es muy variable; la duración puede ser desde unas pocas horas hasta varios días, aunque generalmente varía entre 2 y 8 días.

El período de estas olas es mayor que la de una ola común y varía en aproximadamente 15 a 20 sg, la velocidad en mar profundo puede alcanzar los 12.5 cm/sg.

Los meses de mayor ocurrencia de Bravezas en el Perú son de Abril a Setiembre con un máximo durante el mes de Mayo, debido al cambio de estación. En Invierno la frecuencia de ocurrencia de Bravezas es también alta. En el caso específico del Callao observamos un máximo de 5,300 horas de Bravezas, durante el mes de Mayo, en un lapso de 29 años, lo que representa, aproximadamente, el 25% de ocurrencia eb este período. En Enero, aproximadamente el 5% de los 29 años se produjeron Bravezas.

Los problemas que ocasionan las Bravezas del Mar en las costas del Perú van a depender del estado de la Marea e indudablemente de la intensidad del oleaje. Si bien es cierto que existen años en donde las Bravezas se producen con mayor o menor frecuencia el porcentaje de ocurrencia, como hemos visto, es bastante alto. Normalmente estas Bravezas ocasionan pérdidas económicas al paralizar las actividades en un puerto. En algunos años con la presencia del fenómeno de "El Niño," las Bravezas son aparentemente más destructivas, debido a que en esos años los niveles del mar se incrementan. Las Bravezas que se presentaron durante el evento cálido de "El Niño" de 1982-83, cuando el nivel del mar subió 40 cm sobre su nivel medio, originó no sólo el cierre de puertos sino también muchas áreas inundadas, con los consiguientes daños en las infraestructuras costeras.

INFLUENCIA DE LAS MAREAS EN LA ALTURA DE OLA

El conocimiento de las Mareas reviste gran importancia para los navegantes y para las construcciones de cualquier tipo de infraestructura costera. Cada puerto edita su tabla de mareas que proporciona su altura cada día durante el año.

Las Mareas son movimientos periódicos y alternativos de ascenso y descenso del mar producidos principalmente por atracción gravitacional que sobre la Tierra ejercen el Sol y la Luna y también por la aceleración de su rotación. Las Mareas de mayor altura (sicígias) se producen en Luna llena y Luna nueva, cuando el Sol y la Luna entran en conjunción, sumándose los efectos de atracción de ambos astros sobre la masa de agua.

La Luna no está siempre a la misma distancia de la Tierra, lo mismo ocurre con el Sol. No todos los océanos tienen la misma forma ni las mismas dimensiones. En ciertos mares, las olas de marea entran en resonancia y se amplifican considerablemente, en otras por el contrario se neutralizan entre si, de suerte que el flujo y reflujo son casi inexistentes. La amplitud de la marea, es decir, la altura que separa la pleamar de la bajamar, va a depender entonces de muchos factores. En el Mediterráneo es de pocos centímetros solamente, mientras que en la bahía de Fundy, en Nueva Escocia (Canadá), alcanza más de 15 metros. En el caso del Perú las amplitudes máximas de marea pueden llegar hasta 2.50 metros.

Para el presente estudio se ha utilizado como información básica, el promedio de una serie larga de tiempo de las pleamares más altas observadas durante el mes, es decir un registro por mes; y las pleamares máximas superiores, como el promedio de una serie larga de tiempo, de la máxima pleamar observada en un día, es decir 30 registros por mes, para todos los puertos en estudio y referenciados al nivel medio del mar (Cuadro 1).

Estas ocurrencias de mareas sumadas a la frecuencia de Bravezas, hacen que un porcentaje relativamente alto, pueda coincidir, produciendo problemas frecuentes en el litoral.

DELIMITACIÓN DE LAS ZONAS INUNDABLES

El comportamiento de las olas en tierra son bastante complejas, porque influyen sobre ellas varios factores que se conjugan de diversos modos. Sin embargo la batimetría y sobre todo la topografía son informaciones básicas que permiten delimitar las zonas inundables con cierto nivel de confianza.

En este sentido, observaciones efectuadas en Japón, Hawaii, Alaska y California sobre zonas inundadas por Tsunamis aportan valiosas experiencias. En los lugares mencionados, en muchas ocasiones, las zonas inundables han coincidido con la curva topográfica cuya cota es aproximadamente igual a la altura de ola del Tsunami en la costa.

CUADRO 1. PUERTOS EN ESTUDIO Y REFERENCIADOS AL NIVEL MEDIO DEL MAR

Puertos	**Pleamar Más Alta Observada** (m)	**Pleamar Máxima Superior** (m)
Paita	1.14	0.75
Salaverry	1.44	0.51
Chimbote	1.34	0.47
Callao	0.77	0.36
Pisco	0.79	0.38
San Juan	0.91	0.36
Matarani	0.91	0.41
Ilo	1.05	0.44

De lo anterior puede concluirse que, un estimado inicial de la zona inundable por la ola abarca hasta la cota del terreno cuya altura es igual a la altura de la ola en la costa, pero debe corregirse por efectos de la pendiente del terreno, la posible convergencia o divergencia del frente de onda causada por la topografía de la costa y las diferentes estructuras (muelles, rompeolas, diques, edificaciones, etc.) que frenan a la ola restandole energía.

La pendiente influye de manera importante en la penetración de la ola en tierra. Cuando la franja de terreno es angosta y la pendiente es relativamente fuerte, la extensión de la zona inundada no es muy grande, pero la altura de la zona inundable es mayor que la altura de la ola en la costa. En cambio, cuando el terreno es casi plano, la penetración puede ser mayor, pero la máxima cota que alcanza es menor que la altura de la ola en la costa, lo que hace pensar que en este caso las pérdidas por fricción en tierra son bastante significativas.

En esta primera parte del estudio se asume que la zona inundable abarca hasta la cota del terreno cuya altura es igual a la altura de la ola en la costa. En las primeras observaciones efectuadas no se han considerado aún datos de pendientes de costa. Sin embargo, conociendo las características morfológicas del litoral, se puede asumir este criterio con bastante precisión.

PROCEDIMIENTO

El estudio comprende varias etapas en función del nivel de la aproximación y del impacto económico y/o social en diferentes puntos de la Costa Peruana de acuerdo a las siguientes prioridades:

- **1era. Etapa:** Análisis preliminar de la información disponible.
- **2da. Etapa:** Puertos principales donde se concentra la actividad comercial y una sociedad dependiente de dicha actividad.
- **3era. Etapa:** Puertos secundarios cuya actividad principal es la pesca industrial y una población dependiente de esta actividad.

- **4ta. Etapa:** Puertos menores o caletas donde la actividad principal es la pesca artesanal.

- **5ta. Etapa:** Puntos de la costa donde se desarrollan actividades de maricultura, deportiva, recreación, etc.

Análisis cuantitativo y cualitativo de la información estadística disponible y en algunos casos, cuando fue necesario, se realizaron estimaciones basadas en la experiencia de técnicos relacionados con el tema.

La primera etapa comprendió la evaluación de la información disponible sobre los siguientes puertos principales en la costa peruana: Paita, Salaverry, Chimbote, Callao, Pisco, San Juan, Matarani e Ilo.

RESULTADOS

PAITA

LATITUD	05°05' S	LONGITUD	81°07' W
PLEAMAR MÁXIMA	1.14 m	INCREMENTO	2.14 m
POBLACION	13,000 h		

El terminal marítimo de Paita cuenta con un muelle de atraque de 365 metros de largo por 36 metros de ancho, construido de concreto armado y defensas de pilotes de madera con amortiguadores de caucho. Posee cuatro amarraderos, dos de 165 metros y dos de 200 metros de largo. Se pueden atender buques de calado de hasta 9.5 metros. En cuanto a su infraestructura, posee almacenes y tanques de agua potable entre otros. El puerto está parcialmente protegido hacia el oeste. Es el mejor puerto abierto de la costa peruana y nunca se cierra a causa de mal tiempo. Su población se encuentra ubicada al oeste del muelle principal.

La máxima altura de la ola es de aproximadamente 0.50 m y en casos de braveza de mar esta puede llegar a 1.20 m, esta máxima altura sumada al incremento de 2.14 m nos estaría dando una altura máxima de 3.34 m sobre el nivel medio del mar. Actualmente algunas edificaciones se encuentran construidas por debajo de ese nivel.

SALAVERRY

LATITUD	08°13' S	LONGITUD	78°59' W
PLEAMAR MÁXIMA	1.44 m	INCREMENTO	2.44 m
POBLACION	15,000 h		

Salaverry es un puerto de carga de material. Para la atención a las naves y a la carga, el terminal cuenta con puertos de atraque y almacenes, además de un edificio administrativo para el control de las operaciones portuarias.

Existen dos muelles con cuatro amarraderos para la atención de carga seca, cada muelle tiene 225 m de largo por 25 y 30 metros de ancho respectivamente.

Para la atención de carga líquida, dispone de la instalación de tuberías en el muelle número 1 para el embarque de melazas y alcoholes; para la descarga de petróleo y derivados está instalada una tubería submarina de 700 m de largo de propiedad de PETROPERU. También posee áreas de almacenamiento para carga general y un sistema mecanizado de dos fajas que trasladan el azúcar desde el almacen al muelle.

Salaverry está situado dentro de una vasta zona de playas de arena rodeada de cerros más o menos altos, tanto hacia el lado Este como al Sur: hacia el Oeste de la playa se encuentra establecida la población.

Las alturas de olas en el mencionado puerto se encuentran reducidas por las numerosas defensas construidas para evitar el arenamiento y el oleaje, sin embargo éstas pueden alcanzar una altura de 0.50 m y en casos de braveza hasta 1.00 m, esta máxima altura sumada al incremento de 2.44 m nos estaría dando una altura máxima de 3.44 m. En la actualidad no existe infraestructura por debajo de dicho nivel.

CHIMBOTE

LATITUD	09°05' S	LONGITUD	78°38' W
PLEAMAR MÁXIMA	1.34 m	INCREMENTO	2.34 m
POBLACION	50,000 h		

El puerto de Chimbote posee más de tres muelles, el más antiguo fue construido en el año 1945. La altura de la plataforma en pleamar es de 2.36 y 2.13 m para los dos principales muelles respectivamente. El terminal Marítimo está ubicado en el sector norte de la bahía de Ferrol, protegido por tres islas que conforman dos canales de entrada. La infraestructura de apoyo a los muelles consta de tuberías submarinas, almacenes, equipos mecanizados entre otros.

La altura de ola puede alcanzar hasta 0.70 m, y en casos de braveza de mar las olas llegan hasta 1.20 m, lo que sumado al incremento nos da una altura máxima de 3.54 m sobre el nivel medio del mar. El problema que presenta Chimbote es la amplificación de la onda mareal y la ola debido al fenómeno de resonancia Seiche, que se produce en una bahía tan cerrada. Este fenómeno, aunque no está muy bien estudiado, puede causar mayores problemas de inundación por lo que el puerto podría verse fuertemente afectado.

CALLAO

LATITUD	12°03' S	LONGITUD	77°09' W
PLEAMAR MÁXIMA	0.77 m	INCREMENTO	1.77 m
POBLACION	560,000 h		

El puerto de Callao cuenta con ocho muelles para atraque directo. Existen 21 amarraderos en los muelles, dos rompeolas norte y sur de 2175 m y 1090 m respectivamente. En la parte superior del edificio de operaciones se encuentra el reservorio de agua con capacidad de mil metros cúbicos que dota de agua a las instalaciones portuarias, así como a las naves que atracan en los muelles. El puerto está protegido por el sur por el litoral de Chucuito, La Punta y la isla San Lorenzo.

La altura de ola puede alcanzar 0.80 m y en épocas de braveza esta alcanza hasta los 3.00 m. El incremento de 1.77 más la máxima altura estimada alcanzaría los 4.77 m sobre el nivel actual del mar. Si bien es cierto que gracias a las estructuras de defensa, el Callao se encuentra bastante protegido, Chucuito y La Punta se verían fuertemente afectadas.

PISCO

LATITUD	13°43' S	LONGITUD	76°14' W
PLEAMAR MÁXIMA	0.79 m	INCREMENTO	1.79 m
POBLACION	54,000 h		

En Pisco se encuentra el terminal marítimo de San Martín. Este terminal está ubicado en las tranquilas aguas de la Bahía de Paracas. El nuevo terminal consiste en un muelle marginal de 700 m de largo por 20 m de ancho.

La altura de ola es pequeña debido al poco fondo existente cerca a playa. En época de braveza ésta puede alcanzar excepcionalmente hasta 2.00 m de altura que sumado al incremento nos dá una altura máxima estimada de 3.79 m sobre el nivel medio del mar. En la actualidad es probable que la ciudad de San Andrés se vería afectada, al igual que muchas instalaciones que se encuentren por debajo de dicho nivel.

SAN JUAN

LATITUD	15°21' S	LONGITUD	75°09' W
PLEAMAR MÁXIMA	0.91 m	INCREMENTO	1.91 m
POBLACION	15,000 h		

El puerto de San Juan consta de un muelle de atraque, construido para atender los embarques de hierro de la mina Marcona. San Juan inició sus operaciones en 1953, pero actualmente todo el hierro es embarcado por el puerto de San Nicolás, que se encuentra ubicado 20 km al noroeste.

La altura de ola puede alcanzar en épocas de braveza los 4.00 m, que sumados al incremento alcanzaría los 5.91 m sobre el nivel medio del mar. Este incremento afectaría la parte baja de dicho puerto más no a la mayoría de la población que se encuentra en la parte alta, encima de los acantilados rocosos.

MATARANI

LATITUD	17°00' S	LONGITUD	72°07' W
PLEAMAR MÁXIMA	0.91 m	INCREMENTO	1.91 m
POBLACION	5000 h		

Matarani posee tres muelles de 460, 100 y 90.5 metros de largo, un rompeolas y, faros que se encuentran montados sobre bases de 6 metros de altura. El puerto de Matarani no presenta playas por ser su veril de playa rocoso y acantilado.

La altura de ola en Matarani puede alcanzar en épocas de bravezas más de 4.00 m, que sumadas al incremento nos dá una altura máxima de 5.91 m. Este puerto se encuentra muy bien protegido del oleaje debido al rompeolas existente, lo que impide que sea afectado.

ILO

LATITUD	17°38' S	LONGITUD	71°21' W
PLEAMAR MÁXIMA	1.05 m	INCREMENTO	2.05 m
POBLACION	12,000 h		

El puerto de Ilo posee un muelle construido en el año 1970, áreas de almacenamiento, edificios y almacenes. Existe también un muelle al lado sur. Los principales productos que se movilizan son: minerales y harina de pescado. Existen cuatro plantas de harina de pescado, de gas acetileno y oxígeno, y una distribuidora de petróleo, entre otros.

La altura de ola en esa zona puede alcanzar los 4.50 m en épocas de bravezas, lo que sumado al incremento nos daría una altura máxima de 6.55 m sobre el nivel medio actual del mar. Al parecer este puerto se vería seriamente afectado en caso de que se produjera este incremento, tanto a la población como a su infraestructura.

CONCLUSIONES

- En general en las costas del Perú un aumento de un metro en el nivel medio del mar, afectaría a una pequeña parte de la población e infraestructura costera. Sin embargo, los muelles o edificaciones construidas clandestinamente entre los primeros tres metros sobre el nivel medio del mar, sí sufrirían sus efectos.
- Los muelles en general se encuentran construidos entre las cotas de los 3.20 y 3.80 metros con referencia al nivel medio del mar, lo que perjudicaría las operaciones portuarias, ya que cambiarían los objetivos para los que fueron construidos, y existiría el peligro del colapso de su infraestructura.
- Otro efecto bastante importante sería la reducción de áreas de playas. La investigación de este efecto merece otro tratamiento.
- Un efecto indirecto del incremento del nivel del mar sería el aumento de los daños ocasionados por las Bravezas.
- Las Poblaciones costeras se han establecido sin tomar en cuenta la posibilidad razonable de incrementos del nivel del mar, como por ejemplo en casos de Bravezas de mar durante los períodos de más altas mareas, tal como sucedió en diferentes puntos de la costa durante el evento de el Niño de 1982-83.

RECOMENDACIONES

- Es necesario remarcar que en el presente trabajo sse realizan algunos estimaciones, como, por ejemplo, alturas de olas y características de las bravezas que por lo general varían mucho a pocos metros de distancia, al igual que las delimitaciones de las áreas inundadas. Por ese motivo se hace necesario efectuar un estudio detallado sobre la influencia de un posible incremento del nivel del mar, tomando como proyecto piloto el puerto de Pisco por considerarlo una zona bastante vulnerable tanto por la topografía de la costa, como por la concentración de la población. La Metodología del trabajo consistiría en 6 actividades principales:
    - Cálculos de dirección y altura significante de ola en costa, para todos los puertos en estudio, utilizando datos de informaciones del olágrafo, con sus respectivas correciones por refracción y difracción de la ola.
    - Cartografía de las zonas costeras con el gráfico de las cotas de un metro, cinco metros y diez metros; delimitando la zona de máxima inundación en casos de

bravezas que se produzcan en las pleamares más altas observadas y en las pleamares máximas superiores.

  - El inventario de la infraestructura que se ha establecido por debajo de la cota de un metro y de las zonas de máxima inundación.
  - El censo de la población que se ha establecido en las zonas costeras por debajo de la cota de un metro y de las zonas de máxima inundación.
  - Cuantificación del valor de la infraestructura a ser potencialmente afectada.
  - Cuantificación de los ingresos anuales de todas las actividades cuya infraestructura se encuentre potencialmente afectada.
  - Conclusiones y recomendaciones en el corto, mediano y largo plazo.

- Difundir ampliamente entre las poblaciones costeras y especialmente entre sus autoridades, información sobre los cambios climáticos a nivel Local, Regional y Global y sobre sus posibles impactos en las zonas costeras, principalmente en apoyo a la planificación.
- Continuar con el presente trabajo hasta concluir con la evaluación de la totalidad de las zonas costeras potencialmente afectadas por un incremento de aproximadamente un metro sobre el nivel más alto de las altas mareas, priorizando los puertos de interés.
- Implementar mecanismos eficientes como complemento de la legislación vigente, para evitar que en el futuro se establezcan ya sea poblaciones o infraestructura en zonas costeras con riesgo de inundación por incrementos en el nivel del mar.
- Elaborar planes para la reubicación sistemática de las poblaciones y de la infraestructura, como la solución más adecuada y económica en el largo plazo.
- Iniciar la reubicación de las poblaciones y de la infraestructura según prioridades y según se encuentren en situación más desfavorable y/o peligro inminente.

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THE RISING CHALLENGE OF THE SEA FOR POLAND

R.B. Zeidler
Department of Coastal Engineering and Dynamics
Institute of Hydro-Engineering
Polish Academy of Sciences
Gdansk, Poland

G. Toms
Frederic R. Harris B.V., Consulting Engineers, Planners and Economists
The Hague, The Netherlands

ABSTRACT

This paper is the result of the three-month study that assessed the vulnerability of the coastal zone of Poland to accelerated sea level rise caused by global warming. The work comprised extensive review and interpretation of available physical, environmental, and socioeconomic data pertaining to the Polish coastal zone and the derivation of estimates of the losses, risks, and costs of two strategies for responding to accelerated sea level rise. A parallel study was conducted to demonstrate the use of remote sensing and GIS in the vulnerability assessment.

The study was conducted according to the Common Methodology for Case Studies recommended by the Intergovernmental Panel on Climate Change (IPCC, 1991). The Common Methodology was followed very closely throughout the study, with only minor adjustments being made to accommodate the scarcity of data or specific characteristics of the Polish coastal zone.

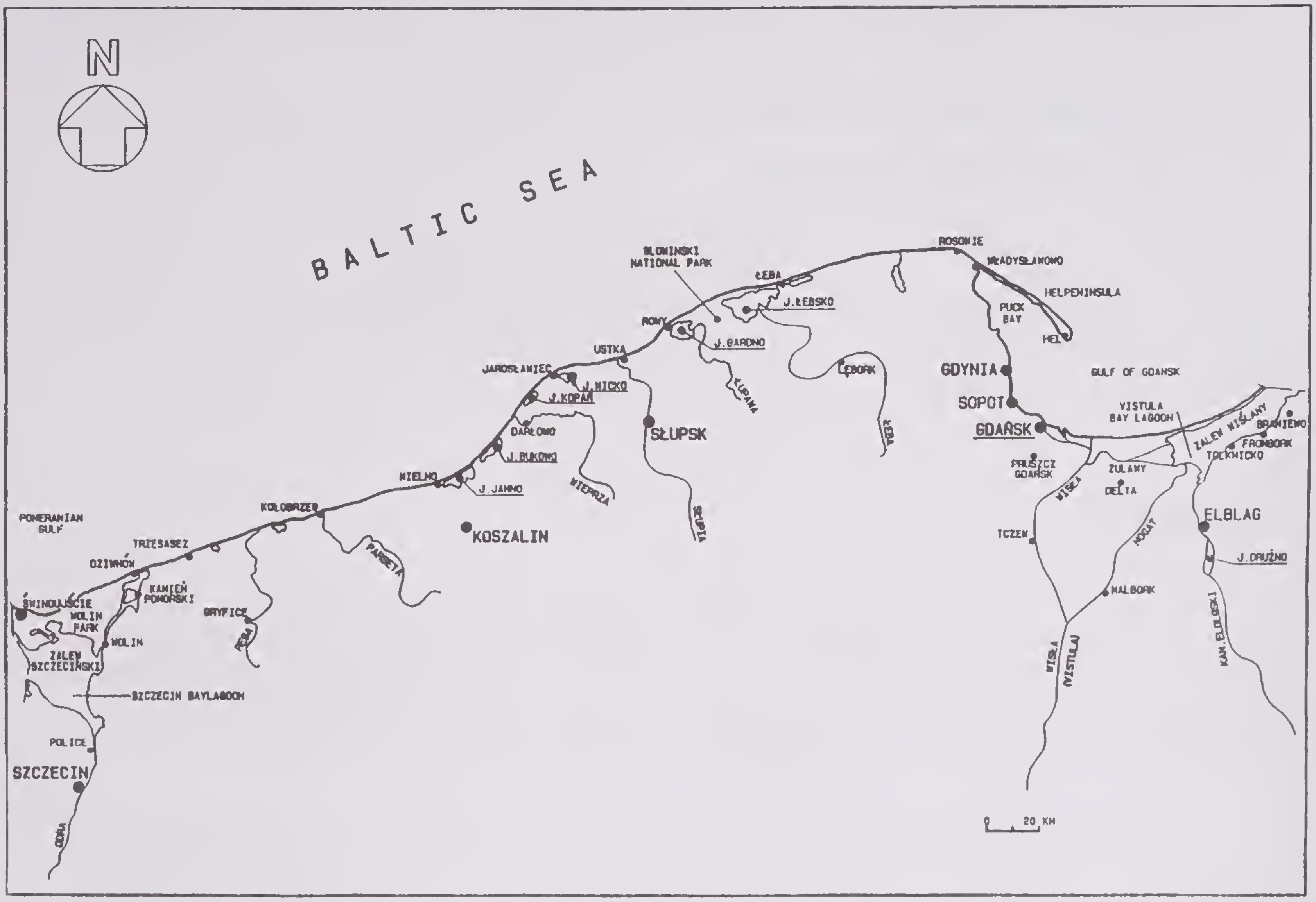
Three visits to Poland were undertaken by engineers from the Dutch working group to work alongside the specialists at the Institute of Hydro-Engineering in Gdansk, where the majority of the data collection and analysis for the project was carried out.

THE STUDY AREA

Poland's 500-km long open sea coastline forms part of the southern limit of the Baltic Sea (Figure 1). The Baltic is a shallow, almost land-locked area. In the region of the Polish coast, tides are negligible, and salinity is low, generally less than 8 parts per thousand. The coastal waters freeze only during the most severe winters, while in summer they may be as warm as 20°C. The Polish coast forms two major gulfs: the Pomeranian Gulf in the west and the Gulf of Gdansk in the east (Figure 1). Two major estuarine systems associated with these gulfs are the Odra River in the west and the Vistula River in the east. Two major lagoons exist, connected with the sea by narrow straits: the Szczecin Bay Lagoon, separated from the sea by the islands of Wolin and Uznam, and the Vistula Bay Lagoon, separated from the sea by the Vistula Spit.

The study area was defined as the area within which the physical effects of the accelerated sea level rise over the next century could be felt, along the entire Polish coastline. The inland boundary of the study area was chosen as the +2.5-meter contour, defining a strip of land along the open coast and low-lying areas adjacent to the coastal lakes, lagoons, and rivers.

FIGURE 1. COASTLINE OF POLAND



The total study area is 2,233 km^2. Figure 2 distinguishes the low-lying areas of the coastal zone. It is clear that the Vistula River delta area and the Odra River estuary comprise the majority of the low-lying areas along the Polish coast.

PHYSICAL CHARACTERISTICS

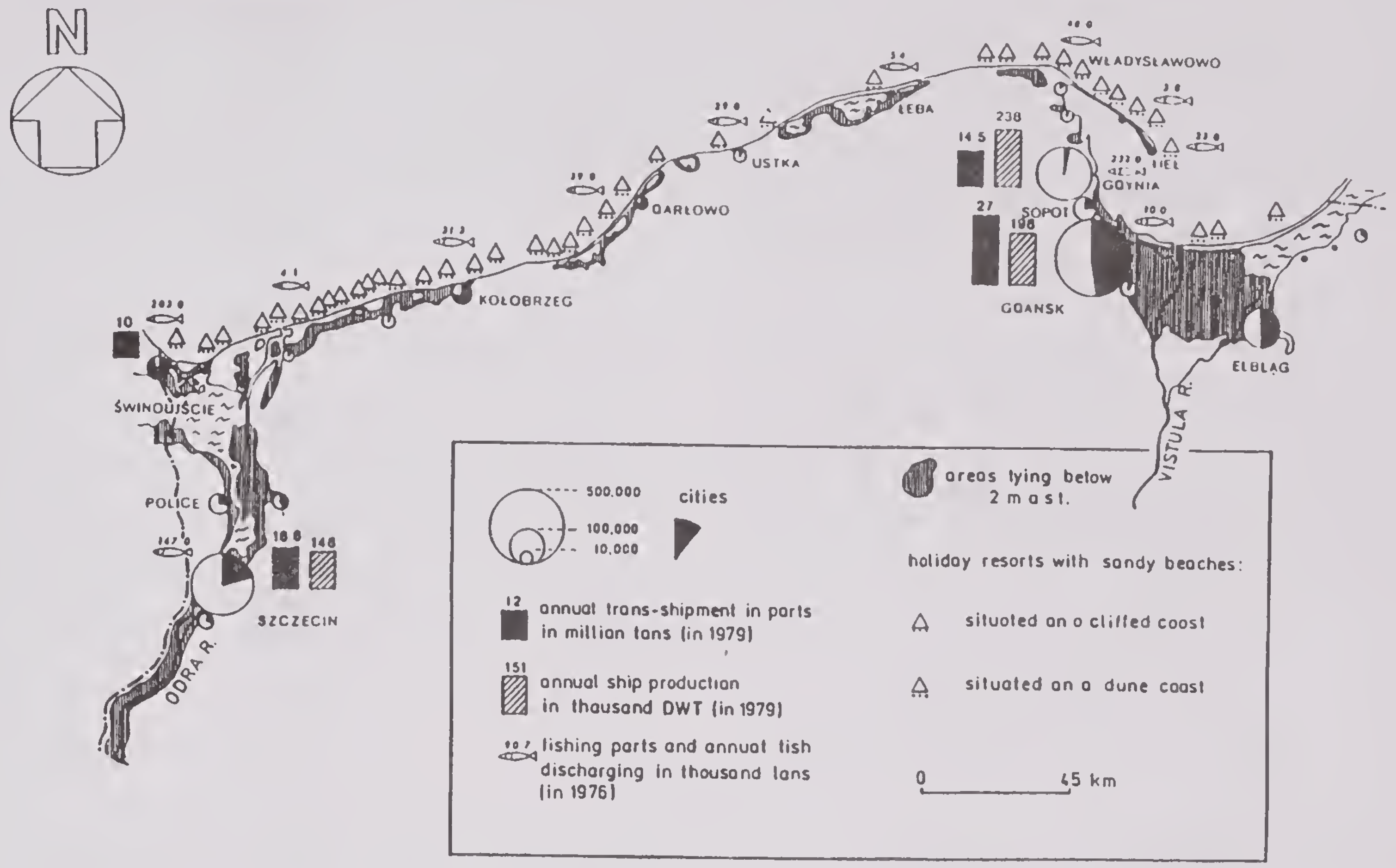
COASTAL TYPES

Dunes occupy about 80 percent of the Polish coastline, and the remainder is fronted by cliffs. Coastal barriers between the sea and coastal lakes are well developed in the central part of the coast. About 20 percent of the open coast is protected artificially ("engineered"), whereas the majority of the estuaries and rivers are protected by dikes.

SUBSIDENCE

The rate of natural subsidence is less than 1 mm/yr. Despite extraction of ground water and other activities in the polder areas, there is no detectable man-made subsidence in the study area.

FIGURE 2. CITIES, PORTS, SHIPYARDS, AND HOLIDAY RESORTS ON THE POLISH BALTIC COAST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HEL
GDYNIA
SOPOT
GDANSK
ELBLĄG
VISTULA R.
10
14 5
238
27
198
186
148
500.000
100.000
10.000
cities
12
annual trans-shipment in ports in million tons (in 1979)
151
annual ship production in thousand DWT (in 1979)
fishing ports and annual fish discharging in thousand tons (in 1976)
areas lying below 2 m a s l.
holiday resorts with sandy beaches:
situated on a clifted coast
situated on a dune coast
0
45 km

(Rotnicki & Borowka 1989)

MEAN SEA LEVEL

The measured trend in long-term (centuries) mean sea level is a maximum rise of 2 mm/year as part of a general rise since the mid-19th century. Medium-term (decades) oscillations have also been identified, such as a fluctuation of about 7 cm within an 11-year period. A surplus in precipitation and river discharge over the outflow of the Baltic to the North Sea has set up a steady sloping of the water surface from east to west along the Polish coast. Gdansk is about 9 cm above that at Swinoujscie. In certain shorter-term surge conditions, larger differences in local areas have been observed, such as the 20-cm difference from the inside (bay) to the outside (sea) of the Hel Peninsula.

DESIGN WATER LEVEL

There is no firm standard for designing the water levels of coastal structures in Poland. However, a 1,000-year return period is recommended for heavily populated areas, and 100 years for less populated areas. Using a data set comprising maximum annual water levels at Gdansk from 1886 to 1975, extreme water levels were derived, as shown in Table 1. The surges during storm events over the Baltic Sea cause these extreme water levels, particularly during strong

TABLE 1. PHYSICAL CHARACTERISTICS OF THE POLISH COAST

Physical Characteristics	**Value**
Total length of study area coastline	*1,040 km*
Additional length of lagoon, lake and river coast	540 km
Total length of open coast	500 km
Coastal types on the open coast	
High cliff in front of high backshore	82.1 km
High broad dune in front of high backshore	247.7 km
Narrow/low dune in front of low backshore	84.3 km
Low coast without dikes	36.3 km
Narrow/low dune in front of low backshore, including low-lying lake	33.6 km
Rivers (alongshore at mouth to sea)	2 km
Ports and harbors (alongshore, open to sea)	14 km
Total length of engineered coast included in study area	*488.7 km*
Length of engineered open coast	116.3 km
Sea walls	18.5 km
Revetments	4.9 km
Groin protected	80.6 km
Offshore breakwater protection	0.6 km
Artificial beach nourishment	12.3 km
Length of engineered river/lake/lagoon coast	372.4 km
Dikes	336.3 km
Sea walls	3.7 km
Revetments	22.8 km
Artificial beach nourishment	9.6 km
Subsidence	
Geological effects	<1 mm/yr
Man-induced subsidence	<1 mm/yr
Mean sea level rise (last century and present)	*+1.5 to +2 mm/yr*
Fluctuations in mean sea level	
20-year cycle	0.03 m
11-year cycle	0.07 m
Alongshore change	0.09 m
Design water level range (lower 100-yr to upper 1,000 yr)	1.4 to 2.0 m
Flood-prone area (low-medium-high estimates, within study area)	*700-1,200-1,700 sq. km*
Average tidal range	*0.01 to 0.1 m*
Average annual wave climate	
Wave height (Hs)	0.4 to 0.5 m
Wave period (Ts)	3.7 to 5.0 s
Design wave height (Hs)	
Offshore of open coast (deep water) e.g., 1 in 10 years	11 m
Shallow water depth limited wave height (Hs)	1.6 m
For all rivers combined	
Sum of all average annual discharges	1,673 cumecs
Sum of all peak discharges	12,100 cumecs
Sum of average annual sediment loads	1,914 to 1,936 ktons
Area with potential salinity problem	*2,500 sq. km*

northwesterly to northeasterly winds. These levels can be further aggravated by local setup in the coastal lagoons due to strong winds (up to 80 cm in the shallow Vistula Bay Lagoon).

FLOOD-PRONE AREA

The area prone to flooding depends on the definition of flooding and the frequency of the flood event. The range of 700–1,700 km^2 given in Table 1 encompasses the most probable and appropriate estimates, depending upon assumptions concerning the viability of the dikes and coastal defenses.

TIDES AND WAVES

Tides in the Baltic Sea at the Polish coast are negligible—about 1 cm in range at Gdansk. However, waves can be considerable during storms. Few measurements exist, but using wind hindcasting methods, a 10-year return period wave height (Hs) was estimated as 11 meters in deep water. Apart from harbor breakwaters, all of Poland's coastal defense is situated at the shoreline and is fronted by a natural beach slope of about 1 in 100. Consequently, the wave height attacking shoreline structures is a maximum of about 1.6 meters.

RIVERS

About 99.7 percent of Poland is drained toward the Baltic Sea; 3.9 percent is drained by the Vistula River with an annual average discharge of 1,000 cumecs. The Vistula contributes about half of the total sediment discharge to the Polish coast.

SALINITY

Due to the low salinity of the Polish nearshore surface waters of the Baltic Sea (7–8 parts per thousand) and the net outflow of water from the coast, saltwater intrusion and associated damage are not serious problems at present in Poland. However, published estimates of the area prone to saltwater intrusion during extreme storm surges indicate that as far as 160 km upstream in the Odra and 50 km upstream in the Vistula, low levels of saltwater intrusion may be detected. Therefore, the study used a rather high estimate of 2,500 km^2 (see Table 1).

HABITATS AND SPECIES

Table 2 summarizes the major habitats and species along the Polish coast.

COASTAL WATERS

Increased nutrient discharges to coastal waters in the last decades have caused a distinct shift in fish populations and in phytobenthos, particularly in Puck Bay and in the Gulf of Gdansk. Fishing yields remain high.

TABLE 2. HABITATS AND SPECIES ALONG THE POLISH COAST

Type of Data	**Data Value**	
	National	*Study Area*
Coastal waters		
Area	8,500 sq. km	8,500 sq. km
Biodiversity		medium # species/sq. km
Red book data species		low # species
Beaches and dunes		
Area	40 sq. km	38 sq. km
Biodiversity		low # species/sq. km
Red book data species		low # species
Forests		
Area	86,000 sq. km	166 sq. km
Biodiversity		highest # species/sq. km
Red book data species		medium # species
Lagoons, barrier lakes		
Area	550 sq. km	550 sq. km
Biodiversity		medium # species/sq. km
Red book data species		medium # species
Rivers and estuaries		
Area	1,500 sq. km	500 sq. km
Biodiversity		medium # species/sq. km
Red book data species		medium # species
Swamps/bogs		
Area	1,000 sq. km	50 sq. km
Biodiversity		high # species/sq. km
Red book data species		high # species
Nature reserves		
Ecological		2.22 sq. km
Special ecological		5.18 sq. km
Total area nature reserves	3,000 sq. km	7.4 sq. km

Note: "Study area" in this table has been extended to include water areas (coastal waters, lakes, estuaries) for the purpose of comparing coastal habitats with national equivalents.

COASTAL FORESTS

Coastal forests occupy about 10 percent of the study area and display the highest diversity of all habitats. They serve as a habitat for 13 species of amphibians, 5 species of reptiles, 40 bird species, and boar, reindeer, and deer.

COASTAL RIVERS AND LAKES

The smaller coastal rivers contain salmon, while freshwater and saltwater fish abound in the Szczecin Bay and Vistula Bay Lagoons. The coastal lakes serve as freshwater habitats for birds and mammals. The biodiversity of the swamps and bogs associated with the lake areas is similarly abundant.

COASTAL BELT FLORA

The coastal belt is characterized by dune flora backed by forest flora and peat bogs. In the Vistula delta (or Vistula Fens), agriculture has almost completely replaced the natural vegetation, but on the Szczecin plain in the east, herbaceous and brushwood natural vegetation on the peat substrata abound.

NATIONAL PARKS AND RESERVE AREAS

There are 95 reserve areas along 0.3 percent of the Polish coast for protecting fauna and flora. For flora, over 23,000 hectares in the Wolinski and Slowinski National Parks are set aside for protecting forest, lake, and dune habitats. Approximately 25 percent of the flora in these parks are rare species. Only one "Landscape Park" at Puck Bay is formally acknowledged on the Polish coast, with 65 percent of its area being the shallow and polluted waters of the bay. Over 250 bird species are found along the Polish coast, of which roughly 2 percent are permanent residents, 25 percent pass at random, and 50 percent spend winter there only (based on observations at Gdansk). Some rare species are found in the Marta Wisla (Vistula Lagoon). The major reserve areas at Wolin, Slowinski, Puck Bay, and Marta Wisla, as well as at many of the smaller reserves, could be susceptible to significant changes in water level and salinity due to sea level rise.

Slowinski Park

Slowinski Park is the largest of the national parks and one of Poland's most memorable natural landscapes. Included on UNESCO's list of the world's important biosphere reserves, the park's 18,247 hectares are comprised of waters (9,835 ha), swamps (1,410 ha), sands (953 ha) and other areas of ecological importance (1,571 ha). The park has four picturesque lakes with an average depth of about 1.5 meters. The lake shores are covered by thick reed, providing an ideal environment for over 250 bird species. The nesters include such rare species as the white-tailed eagle, black stork, crane, ruff, and eagle owl. During late autumn migration, large flocks of wild geese are seen winging over the lakes. In the winter, ducks and other fowl (including velvet scoters, mergansers, auks, and whooper swans) from northern Europe shelter on the park's warmer southern shores of the Baltic. Mammals are numerous in the park. The lake shores harbor deer and boar, with elk, racoons, and badgers in the surrounding woods. Although the coastal barrier is wide, the park's main threat under accelerated sea level rise could be the higher water level at the mouth of the rivers through which the lakes discharge to sea, causing a change in the hydrodynamics, increased flooding, sedimentation, and changes of habitat.

ANALYTICAL APPROACH

DATA COLLECTION

From the project's inception it was clear that a large amount of well-documented and good-quality data existed from various sources in Poland. One example of this was the paper concerning Poland presented at the IPCC-CZMS workshop in Miami in 1989 (Rotnicki & Borowka, 1989) and the subsequent report (Rotnicki & Borowka, 1991). A variety of maps (topographical, environmental, land-use) are available, as well as detailed reports on the coastal systems supported by consultation with local specialists. Significant sources of information are the collected references, particularly "Pobrzeze Pomorskie" (Augustowski, 1984) which extensively describes many features of the coastal zone.

A further information source were the data held at the offices of the various coastal administrative units. Staff from the Institute of Hydro-Engineering in Gdansk traveled along the coastal regions to each of these administrative units to retrieve large amounts of data, particularly concerning flood records and flood defense structures.

To manage the table entries and manipulation of data, a simple spreadsheet system was used to set up a series of working tables. Data for individual areas remain stored and accessible from these spreadsheets.

SEA LEVEL RISE SCENARIOS

Table 3 describes the boundary conditions that are referred to as ASLR1 (0.3-meter rise in 100 years) and ASLR2 (1.0-meter rise in 100 years). These accelerated rates of sea level rise were recommended in the Common Methodology (IPCC, 1991), based on the findings of the IPCC Working Group I. The ASLR1 and ASLR2 levels represent low and high estimates of sea level rise over the next century. The actual rate depends on a multitude of factors, including the degree of success in limiting the global emission of greenhouse gases (CO_2, CH_4, N_2O, and CFCs) and the rate of depletion of the ozone layer.

TABLE 3. BOUNDARY CONDITIONS RELATED TO SEA LEVEL RISE AND CLIMATE CHANGE

Boundary	**Sea Level Rise Scenarios**		**Worst Case**
	0.3 m	*1.0 m*	
Accelerated sea level rise			
Sea level increase 2100 (m)	0.3	1	(1.5)
Maximum rate of change (mm/yr)	3.5	15	(22.5)
Possible other conditions			
Increase in storms (%)			(10)

Note: The worst-case scenario is not dealt with in this case study and requires further investigation.

Only accelerated sea level rise (ASLR) was considered in this study. Other possible effects of climate change, such as local increases in precipitation, increased frequency of Baltic storms, and changes in ambient temperature, were not studied. These can only be quantified after further studies of the regional effects of climate change, using sophisticated climate models. Possible positive effects of climate change (less freezing at river mouths, increased biological productivity of coastal waters, etc.) have also not been quantified in the study and require further attention, although these are expected to be minor in comparison with the negative effects.

For the purposes of this study, the Polish coast was split into four major areas, each with distinct features: (1) the Odra Estuary and the city of Szczecin, (2) western dunes and barrier beaches, (3) central-east dunes and barrier beaches with the Hel Peninsula, and (4) the Vistula delta, including the three-city complex of Gdansk, Gdynia, and Sopot. (See Figure 3.) This division coincides with the administrative division of the Polish coast under the jurisdiction of the Maritime Offices.

FIGURE 3. HYDROLOGIC DATA OF SELECTED REGIONS OF POLAND'S COAST

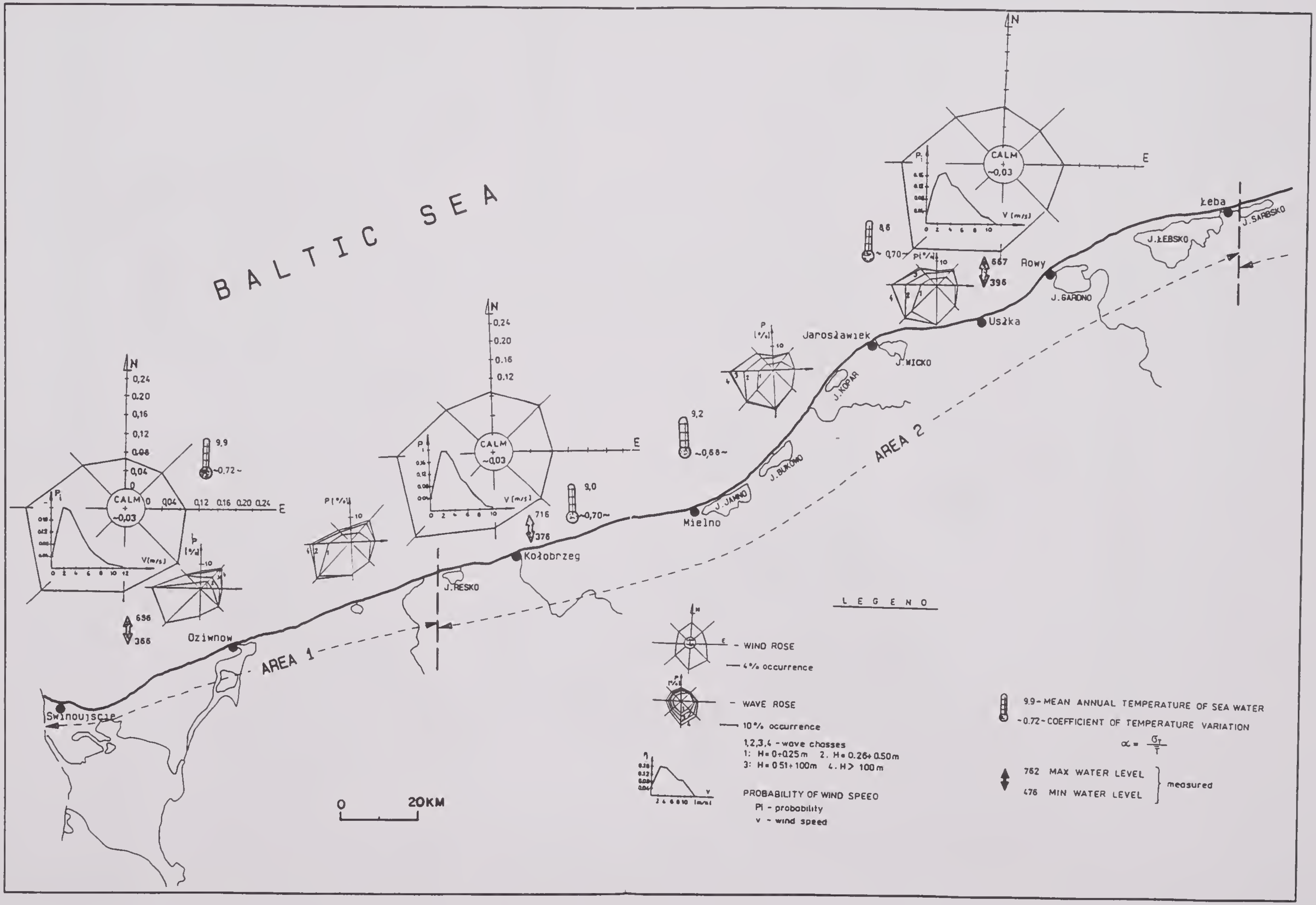
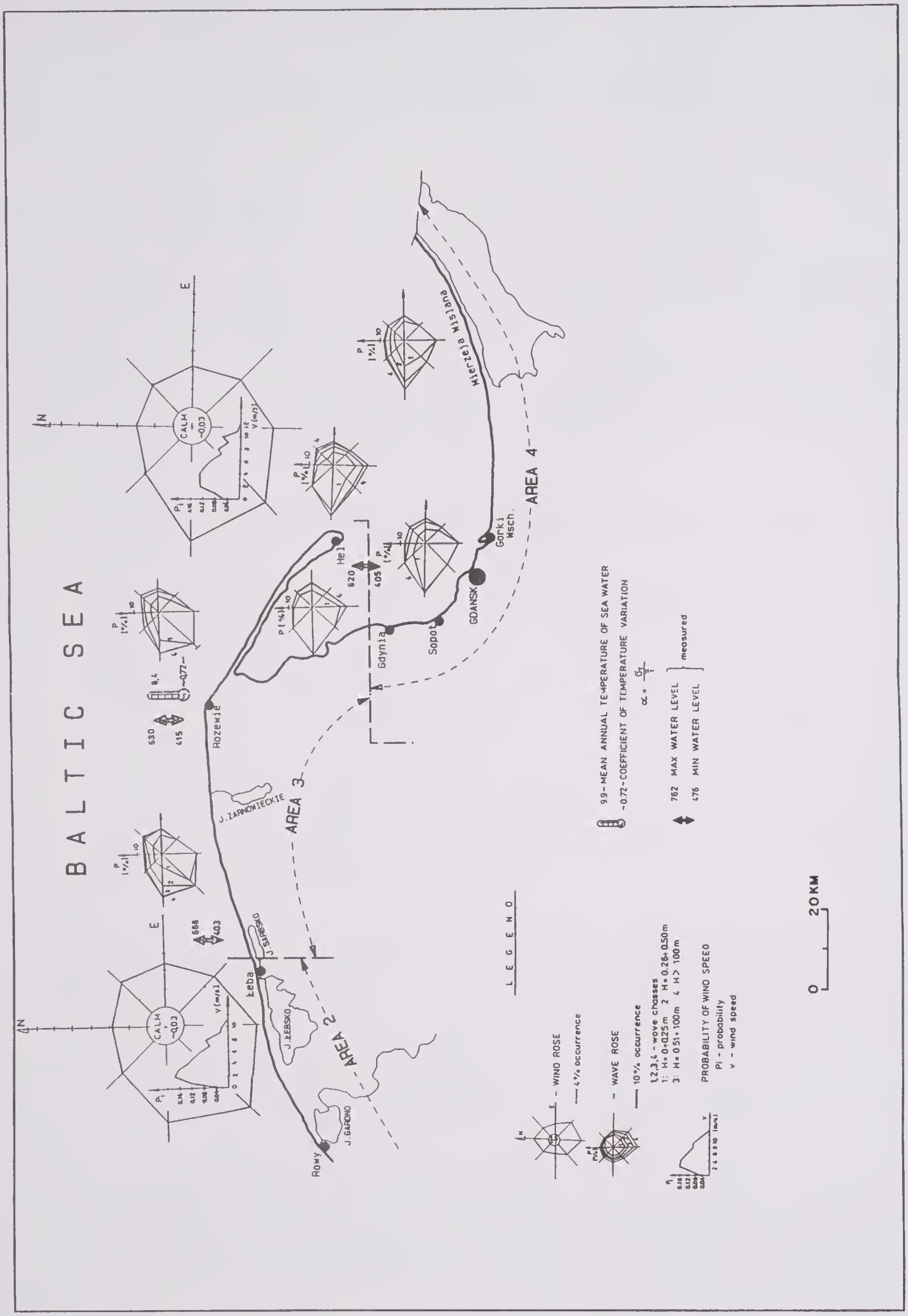
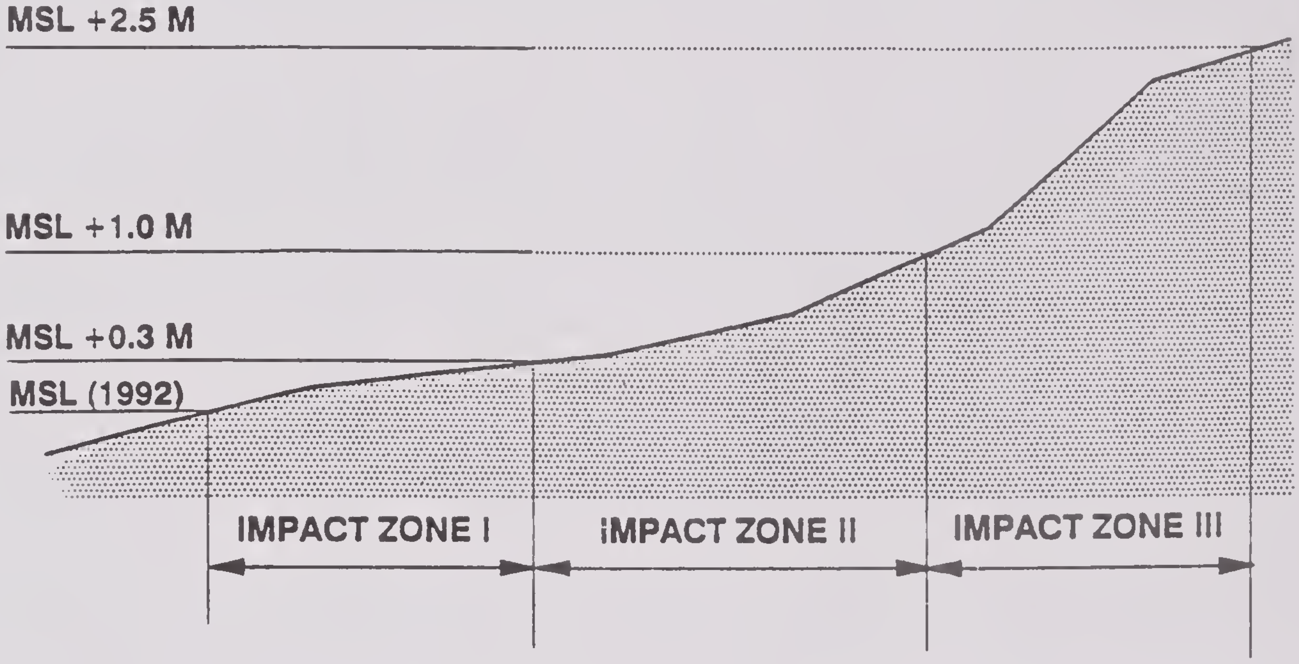


FIGURE 3. HYDROLOGIC DATA OF SELECTED REGIONS OF POLAND'S COAST



To provide a convenient basis for data collection and flood assessment, the study area was further subdivided into impact zones according to mean sea level (MSL): I (0.0 to +0.3 meters MSL, including depressions); II (+0.3 to +1.0 meters MSL); and III (1.0 to +2.5 meters MSL), as depicted in Figure 4. The +2.5-meter inland boundary was chosen because it represents the water level achieved by a 100-year return period storm surge (1.5 meters) acting on an accelerated sea level rise of 1.0 meter.

FIGURE 4. DEFINITION OF COASTAL IMPACT ZONES



SOCIOECONOMIC DATA

MONETARY BASIS

The Polish economy suffered for many years from "stagflation"—stagnant growth and very high inflation. A shock therapy that aims to drastically reduce state expenditures and inflation and stimulate growth is being conducted with the support of the International Monetary Fund (IMF). There are signs that the policy is working and that in the early 1990's some positive growth of the gross domestic product (GDP) will occur (Netherlands Ministry of Economic Affairs—EVD, 1990). Poland is experiencing an era of very high inflation, transition from a state-controlled to a free-market economy, and an exploding exchange rate (from Zl 198/U.S.$ in 1986 to Zl 15,295/U.S.$ in March 1992). For the purposes of this study and Table 4, the equivalent conversions between the Zloty, the U.S. dollar, and the Dutch florin have been used as follows:

U.S.$ 1 = Zl 10,000 **Dfl 1 = Zl 5,700**

This is further convenient, since the issue of a new Polish Zloty with a value of 10,000 present Zloty is being considered by the authorities in Poland.

TABLE 4. SOCIOECONOMIC SYSTEM DATA: GENERAL INFORMATION

Type of Data	**Data Value (Present)**		**Data Value (30 years)**		**Units**
	Nation	*Study Area*	*Nation*	*Study Area*	
GDP	1,000	6	1,767	14.8	10^{12} ZI
	100	0.6	177	1.5	10^{9} US$
	175	1.1	310	2.6	10^{9} Dfl
GDP/capita	26	26	39	40	mill.Zl/ca.
	2,618	2,618	3,927	4,000	US$/ca.
% contribution to GDP					
Agriculture & fishery	12	30	10	15	%
Forestry	1	1	1	1	%
Construction	8	20	10	25	%
Transportation	13	10	15	10	%
Industry	44	15	40	20	%
Services, trade, etc.	22	24	24	29	%
Population					
Area 1	38,200	234.9	48,000	370	thousand people
Area 2	–	67.7	–	106	thousand people
Area 3	–	14.2	–	23.2	thousand people
Area 4	–	143.1	–	225.5	thousand people
Land area	312.7	2.2	312.7	2.2	10^{3} sq. km
Land-use areas					
Agriculture	150	1.93	100	1.3	10^{3} sq. km
Forestry	86	0.2	86	0.3	10^{3} sq. km
Fisheries	2	0	1.7	0	10^{3} sq. km
Industry	5	0.01	10	0.2	10^{3} sq. km
Recreation	28	0.01	50	0.2	10^{3} sq. km
Urban	20	0.02	30	0.05	10^{3} sq. km
Rural	18	0.1	25	0.1	10^{3} sq. km
Nature reserve	3	0.01	10	0.05	10^{3} sq. km
Subsistence population	0	0	0	0	#
Capital value	120,000	450	426,000	2,3000	10^{12}ZI
	12,000	45	42,600	230	10^{9}US$
	21,100	79	74,550	403.5	10^{9}Dfl
Capital value/sq. m	384,000	204,000	1,362,328	1,045,500	Zl
	38.4	20.4	136	104.5	US$
	67.4	35.8	238	183	Dfl
Growth (avg. 30 yrs)					
GDP	1.9	3	–	–	%/yr
Population	0.8	1.5	–	–	%/yr
Capital value	4.3	5.6	–	–	%/yr

Note: The capital values for the study area have been calculated using the detailed distribution of land-use areas and capital values in Table 4. For the nation, average values were assigned to the land-use categories in this table.

GROSS DOMESTIC PRODUCT

The adopted figure of U.S. $100 billion was consistent with the quoted GDP from the Netherlands Ministry of Economic Affairs (EVD, 1990) and the Economic Intelligence Unit, UK (EIU, 1991) reports. The Polish GDP/capita was U.S. $2,618 in 1989. The contribution of various land-use activities to the national GDP was obtained from the *Concise Statistical Yearbook,* with 44 percent contributed by industry, and 12 percent by agriculture. The study area GDP was estimated from the national figure by use of the GDP/capita value. The land-use contributions to GDP within the study area were adjusted from the national figures to represent the different trends of the coastal zone—e.g., industry, 15 percent; agriculture, 30 percent.

POPULATION

In 1990, the population of Poland was 38.2 million. For the study area, the population of 234,900 was computed by multiplying the urban and rural land-use areas measured from the topographic maps times the population-density factors derived from the *Yearbook.* Area 4 in the west contained the highest population— 60 percent of the total study area.

LAND USE

Nationally, about 50 percent of Poland is farmland, and 27 percent is forests. In the study area, detailed analyses of 55 topography charts (1:25,000) formed the basis of an inventory of the land-use areas within the impact zones I, II, and III and within the four areas in Table 5. Data were also extracted concerning the lengths of roads, telecommunications, and power lines, so as to include these in assessments of capital losses by inundation.

TABLE 5. LAND USES AND VALUES

TYPE OF DATA	AREA 1	AREA 2	AREA 3	AREA 4	TOTAL
		Data Value: Present			
Surface area in sq. km	597	243	173	1,221	2,234
Comprising land-use types					
Beach & dune (B)	5	7	11	7	30
Agriculture – high value (AH)	3	0	0	1,084	1,087
Agriculture – low value (AL)	423	165	147	21	756
Agriculture – very low value (AO)	56	10	1.2	23	90.2
Forests (F)	90	51	3.5	21	165.5
Recreation (R)	0.4	0	7.4	1	8.8
Nature reserve (NR)	0	4.7	0	2.8	7.5
Rural (W)	5.5	4.8	1.7	38	50
Urban (U)	6.4	0.9	15	23.2	10
Industry (I)	5	0	0	8	13
Harbors (H)	3	0	0	0	3
Roads & communications (km) (T)	220	75	60	660	1,015

TYPE OF DATA	AREA 1	AREA 2	AREA 3	AREA 4	TOTAL
		Data Value: Present			
Unit capital costs in Zlx10^4/sq. m					
Beach & dune (B)	10	10	10	10	--
Agriculture – high value (AH)	2	2	2	3	--
Agriculture – low value (AL)	0.5	0.5	0.5	0.5	--
Agriculture – very low value (AO)	0.2	0.2	0.2	0.2	--
Forests (F)	1	1	1	1	--
Recreation (R)	10	10	10	10	--
Nature reserve (NR)	20	20	20	20	--
Rural (W)	120	120	120	120	--
Urban (U)	700	200	500	900	--
Industry (I)	600	200	300	600	--
Harbors (H)	1,500	1,500	1,500	1,500	--
Roads & communications (km) (T)	900	500	500	900	--

	AREA 1	AREA 2	AREA 3	AREA 4	TOTAL
		Data Value: In 30 Years			
Surface area in sq. km	597	243	173	1,221	2,234
Comprising land-use types					
Beach & dune (B)	5	7	11	7	30
Agriculture – high value (AH)	5	0	30	961	996
Agriculture – low value (AL)	210	20	60	0	290
Agriculture – very low value (AO)	10	5.5	0	0	15.5
Forests (F)	170	80	20	30	300
Recreation (R)	90	70	15	15	190
Nature reserve (NR)	10	20	10	10	50
Rural (W)	22	10	5	53	90
Urban (U)	10	5	5	30	50
Industry (I)	60	25	17	114	216
Harbors (H)	5	0.1	0.1	1	6.2
Roads & communications (km) (T)	230	80	60	700	1,070
Unit capital costs in Zlx10^4/sq. m					
Beach & dune (B)	20	20	20	20	--
Agriculture – high value (AH)	6	6	6	6	--
Agriculture – low value (AL)	2	2	2	2	--
Agriculture – very low value (AO)	0.7	0.7	0.7	0.7	--
Forests (F)	3	3	3	3	--

TYPE OF DATA	AREA 1	AREA 2	AREA 3	AREA 4	TOTAL
		Data Value: In 30 Years			
Recreation (R)	33	33	33	33	--
Nature reserve (NR)	20	20	20	20	--
Rural (W)	250	250	250	250	--
Urban (U)	1,300	600	800	1,500	--
Industry (I)	600	200	300	600	--
Harbors (H)	1,500	1,500	1,500	1,500	--
Roads & communications (km) (T)	1,200	800	800	1,500	--

CAPITAL VALUE

"Capital value" is defined as the total value of the land plus infrastructure, including removables. It was assumed to be equivalent to the replacement value of the complete facility offered by the land plus the land itself. For the nation, the capital value was estimated by multiplying the current market prices per hectare (adjusted to include infrastructure) by respective areas of land use. The derived capital value for Poland was 120 times the GDP, indicating a high capital value but low return in productivity. A comparison between the capital value of Poland/m^2 and that of The Netherlands lent confidence to the derived capital value for Poland: Netherlands Dfl 110-120/m^2, Poland Dfl 32-70/m^2. Unit capital values in the study area are given in Table 5.

Current market prices were researched. An almost balanced market already exists for agricultural land, forests, and some other categories. More variation and scarcer information were encountered for urban areas, particularly industry. Larger lots of established housing or any lots of industry are not yet offered for sale. The results of inquiries made to various property dealers offering smaller houses, workshops, and factories were extrapolated to larger housing and industry categories as the only resort. Therefore, the resulting capital values are first estimates that need refinement in future work. The figures may be an overestimate when totaled for the nation, due to variations in demand and, in the case of some classes, quality.

GROWTH

GDP is expected to show slow positive growth in accordance with a gradual recovery of the Polish economy. A value of 0.4 percent/year for the nation is expected in the next few years. However, a higher growth—1.9 percent/year—has been entered in Table 4 to represent an optimistic average over the next 30 years. This has been elevated further for the study area. The growth in capital value has been set based on the calculated product of estimated 30-year capital values per land-use type and the redistribution of land-use areas.

THE 30-YEAR SCENARIO

Until now, development has been dominated by the concentration of various activities in the deltas of the Odra and Vistula Rivers and urbanization of Szczecin and Gdansk. These areas account for about 50 percent of the investments in the entire coastal region. Gradual expansion of coastal towns, including small fishing and merchant harbors and ports, small shipyards, and recreational resorts has taken place. Medium-size cities, such as Kolobrzeg, also grew around natural links with the sea.

In the future, further growth of the dominant centers is likely to be accompanied by a faster development of other coastal cities and areas of unused potential. In the east (Area 4), Elblag will play an increasingly important role due to its infrastructure, its proximity to the new states of Lithuania, Latvia, and Russia, and its lifting of a former Soviet ban on the use of its access to the sea via the Pilawa Straights. In addition, several small cities, towns, ports, and harbors, such as Tolkmicko, Frombork, Krynica Morska, and Katy Rybackie, can flourish and profit from trade, yachting (ice boating in the winter), tourism, and recreation all along the Vistula Bay. Recreation and tourism will grow, and the harbors of Gdansk and Gdynia will expand. Exploitation of new oil finds off Rozowie could significantly affect use of the north coast. New transportation links with Scandinavia, the new Balkan states, and Czechoslovakia will further stimulate growth.

REDISTRIBUTION OF LAND-USE AREAS

In accordance with these trends, land use is projected to be redistributed during the next 30 years, as shown in Tables 4 and 5. For Poland, one can assume a gradual 10 percent decrease in agricultural area, with the remaining land-use categories expanding. The major decrease in agricultural land is expected to be distributed among urban and rural development, forests, industry, and recreation lands, proportionally to their present areas. Minor portions will also be added to harbors, nature reserves, and fisheries, which altogether occupy a small fraction of Poland's land area. For the study area, more severe cuts in agriculture were assumed. Capital values for the 30-year scenario were based on present-day Netherlands values, which assume a development trend for Poland similar to that of the present-day Netherlands.

POPULATION GROWTH

Table 6 shows the projected national growth of population (*Yearbook*, 1991).

TABLE 6. HISTORIC AND PROJECTED POPULATION IN POLAND

Year	**1960**	**1970**	**1980**	**1990**	**2022**
National population (in millions	29.8	32.7	35.7	38.2	48.0 million
Percentage growth/10 years		9.7	9.1	7.0	8.0

ASSESSING PHYSICAL EFFECTS AND NATURAL SYSTEM RESPONSES

EFFECTS ON EXTREME SEA WATER LEVELS AND FLOODING

Based on the curve fitting used for entries in Table 1, the return periods for key water levels of +0.3, +1.0, and +2.5 meters (at the inland borders of the impact zones) were assessed for the present mean sea level and for the accelerated sea level rise scenarios of +0.3 and +1.0 meters. These were entered in Table 7 as the probability of exceedance of the given water level at least once a year.

TABLE 7. PHYSICAL EFFECTS AND NATURAL SYSTEM RESPONSES: WHOLE COAST SUMMARY

TYPE OF DATA	SEA LEVEL RISE SCENARIOS						Units
	Present Development			30-Year Development			
	Base	*0.3 m*	*1.0 m*	*Base*	*0.3 m*	*1.0 m*	
PHYSICAL EFFECTS							
Shoreline development							
Erosion	0.5	0.8	1.5	0.5	0.8	1.5	m/yr
Accretion	0.1	0.1	0.2	0.1	0.1	0.2	m/yr
Water levels above MSL 100 [1,000] yr return period							
Sea/lagoon	1.5 [1.8]	1.8 [2.1]	2.5 [2.8]	1.5 [1.8]	1.8 [2.1]	2.5 [2.8]	m
River mouth	1.6 [1.9]	1.9 [2.2]	2.6 [2.9]	1.6 [1.9]	1.9 [2.2]	2.6 [2.9]	m
Salinity							
Salt wedge intrusion							
Odra R	100.0	55.0	85.0	55.0	65.0	90.0	km
Wisla R	50.0	55.0	85.0	55.0	65.0	90.0	km
Others	10.0	11.0	15.0	11.0	12.0	16.0	km
Seepage rate							
Max. east	0.1	0.2	0.2	0.2	0.2	0.3	m/yr
Seepage salinity	1.0	1.2	2.0	1.0	1.2	2.0	ppth ave.
NATURAL SYSTEM RESPONSES							
Areas inundated at least once a year = "lost"							
Agriculture–high (AH)	20.2	65.7	872.1	21.0	66.8	854.3	sq. km
Agriculture–low (AL)	97.1	109.2	566.4	64.0	72.0	232.2	sq. km
Agriculture–very low (AO)	25.5	29.4	87.0	6.2	6.8	14.7	sq. km
Forests (F)	11.3	12.7	110.4	23.2	26.1	223.0	sq. km
Recreation (R)	0.0	0.0	1.4	27.2	30.4	140.0	sq. km
Nature reserve (NR)	3.9	3.9	6.9	9.5	10.4	35.7	sq. km
Rural (W)	0.3	0.6	32.5	2.7	3.6	71.9	sq. km
Urban (U)	0.4	0.5	14.3	0.7	0.9	23.4	sq. km
Industry (I)	0.0	0.2	9.4	4.3	5.2	105.4	sq. km
Harbors (H)	0.0	0.0	0.0	0.0	0.0	0.0	sq. km
Roads, etc. (T)	0.6	0.9	7.9	0.6	1.0	8.2	km
Land-based habitats inundated at least once a year = "lost"							
Forests	11.3	12.7	98.3	23.2	26.1	198.0	sq. km
Lagoon, lakes		gain	gain		gain	gain	sq. km
Rivers, estuaries		gain	gain		gain	gain	sq. km
Swamps, bogs (maximum in the west)	15.0	40.0		15.0	40.0	sq. km	
Flooding frequencies (water level exceedance at least once a year)							
+0.3 MSL	100.0	100.0	100.0	100.0	100.0	100.0	%
+1.0 MSL	20.0	65.0	100.0	20.0	65.0	100.0	%
+2.5 MSL	0.001	0.005	0.650	0.001	0.005	0.650	%

Water Resources							
Drainage rates	0.2	0.3	0.3	0.2	0.3	0.3	m/yr ave.
Salinity drainage water	0.5	0.6	0.8	0.6	0.6	0.9	ppth ave.
Freshwater availability	7,060 mil	7,060 mil	7,060 mil	7,100 mil	7,100 mil	7,100 mil	m^3/yr

The percentage of each impact zone within each of the four areas that would be inundated at each of the three water levels (+0.3, +1.0, and +2.5 meters) and for each mean sea level scenario (base–present (no rise), +0.3 meter, and +1.0 meter) was assessed by tracking the possible pathways of inundation due to rising storm-surge level and by identifying vulnerable locations (rivers, channels, enhanced subsurface flow, etc). Table 8 shows the percentages of the corresponding impact zones that would be flooded (with no protective measures) at the given water levels.

TABLE 8. PERCENT OF LAND FLOODED UNDER DIFFERENT SCENARIOS

	Area 1			**Areas 2 & 3**			**Area 4**		
Scenarios	*Base*	*0.3 m*	*1.0 m*	*Base*	*0.3 m*	*1.0 m*	*Base*	*0.3 m*	*1.0 m*
+ 0.3 m (Zone I)	80	90	100	90	90	90	3	10	100
+ 1.0 m (Zone II)	80	80	100	90	90	90	10	10	100
+ 2.5 m (Zone III)	80	80	100	90	90	90	10	10	80

These percentages, multiplied by the probabilities of annual exceedance of mean sea level of +0.3, +1.0, and +2.5 meters, and the areas per impact zone produced the estimates for areas flooded annually (100 percent chance of annual inundation–Table 7) and the areas at risk.

RIVER, LAKE, AND GROUND-WATER LEVELS

Backwater in rivers has been estimated in evaluation of flooding scenarios. For the major rivers, good records exist of previous backwater events during storm surges. In this study, it was assumed that the water level in coastal lakes varies similarly to the sea. Higher sea level will hinder the seaward flow of ground water, and the water table will rise in the coastal zone by the same degree.

WATER RESOURCES

The seepage rate has been estimated to vary from 0.02 m/yr in Areas 2 and 3 to 0.10 m/yr in Area 1 and 0.14 m/yr in Area 4. The drainage rate is taken as the sum of the seepage rate and the difference between precipitation and evaporation. Both seepage and drainage rates have been assumed to vary so slightly within the accelerated sea level rise and 30-year scenarios that the effect is negligible. The freshwater availability has been computed individually for Areas 1, 2, 3, and 4. It was assumed that 20 percent of the river discharge of the given area would be available for irrigation. These amounts have been added to precipitation.

SALINITY

With sea level rise, the lakes would grow more saline as a result of more frequent inflows of Baltic waters into them through river mouths and overwash breaches of barriers. The Baltic itself could become more saline, as a rise in sea level would facilitate exchange between the Baltic and Atlantic through the Danish Straits. The irrigation water is slightly saline due to salt water (e.g., from salt mining upstream) in supplying rivers, and is highest in the Vistula Delta. The available data were averaged to deduce the variation shown in Table 7.

WAVES

Since waves are depth limited, the height of a wave breaking on an existing shoreline structure or beach will rise for a specific location with the rise in mean sea level. A 1.0-meter rise in sea level will increase this design-breaking wave to 2.5 meters, leading to additional damage and erosion.

ASSESSING PROTECTION COSTS

The typical structures used for analyzing costs and measures were new and adapted dikes, new and adapted sea walls, and new and adapted breakwaters and beach nourishment. Existing coastal structures were examined in some detail along the entire coast, replacement or adaptation was considered, and preliminary designs were drawn up. The shoreline lengths covered by each of these types of defense were then deduced following a kilometer-by-kilometer assessment of the appropriate measures along the whole coast. The volume per year of beach nourishment required was estimated as the product of the loss rate (calculated by Bruun Rule and other in-house models) and the shoreline length.

For costing purposes, the structures were grouped into the typical types, and costs were assigned based on an analysis of the current construction prices in Poland. No distinction was made between the unit costs for the 0.3- or the 1.0-meter scenario, implying that the same type of structure would be used for both scenarios.

For the 30-year scenario, present-day Netherlands rates for construction were used to price the proposed Polish sea defenses under the 0.3-meter scenario. For the 1.0-meter scenario, a scaling factor in the cost of the structures was applied to reflect a large increase in crest height and the reconstruction that would be required to bring the Polish coastal defense measures in line with those presently adopted in The Netherlands. This also allowed for the assessment of the sensitivity of the analysis to increased crest height (safety factor). By comparing some typical structures and their associated costs, the scaling of two times was applied to reflect the increase in unit costs for protecting the coast against a 1.0-meter rise, as opposed to a 0.3-meter rise. For the 30-year scenario, no change was made to the protection strategy concerning lengths of protection measures and beach nourishment quantities.

RESULTS

Two response strategies were considered:

1. Taking no action beyond the protection already in place.
2. Fully protecting the coastline.

Table 9 shows the impacts of each of these strategies under the 0.3- and 1.0-meter sea level rise scenarios. The results of Table 9 enable a rough cost-benefit analysis to be made of the coastline as a whole by comparing the costs of protection with the costs of damage. In reality, scarce funds will be allocated on the basis of detailed cost-benefit analyses of specific vulnerable elements of the coast and their perceived importance nationally and regionally. These more detailed analyses can be conducted similarly as the whole coast assessment and should include more in-depth studies of flooding and protection scenarios in the specific local area in question.

TABLE 9. COASTAL SYSTEM VULNERABILITY

Impact Category	**Units**	**Present**	**No Development**		**30-Year Development**	
			0.3 m	*1.0 m*	*0.3 m*	*1.0 m*
			No Action			
Socioeconomic values at loss						
Capital value lost	Zlx10^{12}		9.6	244.0	68.2	1,147
Subsistence value lost	Zlx10^{12}		0	0	0	0
People relocated	x1000		8.5	146.1	10.3	176.3
Socioeconomic values at risk						
People at risk	x1000	9.8	31.7	50.3	41.2	108.5
Capital value at risk	Zlx10^{12}	17.5	56	97.8	325	612
Subsistence value at risk	Zlx10^{12}	0	0	0	0	0
Socioeconomic values at change						
Land-use damage (climate change)	Zlx10^{12}		–	–	–	–
Land-use damage (increased salinity)	Zlx10^{12}		<0.01	<0.01	<0.01	<0.01
Other financial damages	Zlx10^{12}		–	–	–	–
Ecological values at loss						
Ecological areas lost	x sq.km		1.2	3.4	3.1	10.7
Special areas lost	x sq. km		2.7	7.9	7.3	25
Costs of response measures						
Implementation costs	Zlx10^{12}		0	0	0	0
Ongoing maintenance & annual costs	Zlx10^{12}/yr		0	0	0	0
			Full Protection			
Socioeconomic values at loss						
Capital value lost	Zlx10^{12}		1.1	3.5	4	12.4
Subsistence value lost	Zlx10^{12}		0	0	0	0
People relocated	x1000		<0.1	0.1	0.1	1
Socioeconomic values at risk						
People at risk	x1000	9.8	<9.8	<9.8	<12.8	<12.8
Capital value at risk	Zlx10^{12}	17.5	<17.5	17.5	<100.9	100.9
Subsistence value at risk	Zlx10^{12}	0	0	0	0	0

Impact Category	Units	Present	No Development		30-Year Development	
			0.3 m	*1.0 m*	*0.3 m*	*1.0 m*
Socioeconomic values at change						
Land-use damage (climate change)	Zlx10^{12}		–	–	–	–
Land-use damage (increased salinity)	Zlx10^{12}		<0.01	<0.01	<0.01	<0.01
Other financial damages	Zlx10^{12}		–	–	–	–
Ecological values at loss						
Ecological areas lost	x sq.km		1	3	3	10
Special areas lost	x sq. km		2.5	4	7	25
Costs of response measures						
Implementation costs	Zlx10^{12}		5.6	14.6	22	74.8
Ongoing maintenance & annual costs	Zlx10^{12}/yr		0.1	0.4	0.5	1.6

Explanation of entries in Table 9

1. *Capital value lost*: Deduced as the sum of the capital values of areas that would be lost (no action) or abandoned (full protection). In the case of no action, land is lost if the probability of annual inundation is 100 percent.

2. *Subsistence value lost*: There is no substantial subsistence farming in Poland.

3. *People relocated:* In the no action case, this is the population in areas flooded annually. For the full protection strategy, this is the population in areas to be abandoned in the future.

4. *People at risk*: For the no action case, this is the population outside the lost area times the risk of flooding in the remaining area. For full protection, this is the same as the figure for the "present case" with no accelerated rise, since by definition the same level of protection will be afforded. However a "<" sign indicates that the construction of protection against an acceleration in sea level rise will reduce the risk below the present levels.

5. *Capital value at risk*: The capital value of the remaining area times the risk of flooding of the remaining area (for the full protection case the same as the existing risk).

6. *Subsistence value at risk*: Negligible (see 2, above).

7. *Land-use damage due to climate change:* The effects of no acceleration were not considered.

8. *Land-use damage due to increased salinity:* This is expected to be very low. Approximately 5 percent of the agricultural areas (at risk) for a 0.3-meter rise and 10 percent for a 1.0-meter rise.

9. *Other financial damages*: Negligible. Among the damages not assessed in this initial study is the possibility of contamination of the water supply for the coastal cities of Gdansk, Gdynia, Elblag, and Szczecin. This effect could be the most serious of all, but more detailed studies are required.

10. *Ecological values at loss*: These were taken as the sum of nature reserve areas that would be inundated annually with a probability of 100 percent. This sum was then distributed as 33 percent "ecological areas" and 67 percent "special ecological areas." The loss of wetland will not be great, but these losses will be no less important than the others.

11. *Implementation costs of response measures:* These are negligible by definition for the no measures response case. For the full protection case, they are the sum of the initial capital costs of the strategy derived in Table 12 (excluding maintenance).

12. *Ongoing maintenance and annual costs*: These include beach nourishment and a maintenance cost of 2 percent (of initial costs) per year. This is negligible for the no measures case.

IMPACTS AND COSTS OF TAKING NO ACTION

Taking no action against accelerated sea level rise beyond the protection already in place could result in zero implementation costs but maximum damage. About 869 hectares (80 percent of all study area) could be lost. This would include 564 km—126 km of railways, 415 km of primary power lines, and 26 bridges. Table 7 shows what types of land would be lost under the different sea level rise scenarios if no action were taken.

A sea level rise of 0.3 meters over the next century will not cause widespread inundation. However, local areas already stressed by extreme events will be under additional and more frequent pressure. Dikes and sea walls will need to be inspected thoroughly and maintained regularly, particularly those areas most vulnerable to erosion and flooding. Maintenance measures should include replacing aging structures and installing pump stations, etc. In addition, the crest levels of sea walls should be raised to increase the degree of protection.

A sea level rise of 1.0 meter over the next century will seriously flood vulnerable areas, possibly resulting in permanent loss, as quantified in Table 7. These problems will be exacerbated with the more frequent storms expected from climate change. For example, a 1.0-meter rise will cause damage of up to +2.5 meters above the present mean sea level. This damage may be irreversible, as dikes and sea defenses suffer accumulated damage and lose their integrity. This effect is demonstrated by the results of the remote-sensing and GIS analyses of the Hel Peninsula and the Zulawy Delta. A strategy for replacing and upgrading existing protection measures would be essential.

Table 10 shows that property and land losses are expected to be critical for a projected rise of 1.0 meter over the next century if no measures are taken to protect against sea level rise. It expresses losses as a percentage of GDP. (When expressed as a percentage of the nation's capital value, then the losses are classed as low. This is because of the large difference between capital value and GDP). Losses are low for the 0.3-meter rise over the century based on present development, but high for the 30-year development level. For relocation of people, a conservative criterion was used which assumes that relocation will be necessary if an area is flooded once a year. The estimate is also conservative for the 30-year case, where extensive influx of population has been assumed, along with an optimistic scenario of economic growth in the study area. In reality, if no action were taken, the population in low-lying areas would be avoided, but this effect was not taken into account. The resulting relocations reach critical levels for the 30-year scenario and 1.0- meter sea level rise over the next century. Of note is that there is already a medium-risk classification for numbers of people flooded annually. Salinity and ecological areas show low vulnerability, except for medium losses for special ecological areas under the 1.0-meter scenario in 30 years.

TABLE 10. VULNERABILITY ASSESSMENT FOR NO ACTION SCENARIO

Impacts	**No Development**		**30-Year Development**	
	0.3 m	*1.0 m*	*0.3 m*	*1.0 m*
Values at Loss				
Capital value lost (% of nation's GDP)	Low (<1%)	Critical (>10%)	High (1-3%)	Critical (>10%)
Capital value lost (% of nation's CV)	Low (<3%)	Low (<3%)	Low (<3%)	Low (<3%)
People to be evacuated (x1000)	Medium (1-50)	Medium (1-50)	High (50-150)	Critical (>150)
Ecological areas lost (sq. km)	Low (<100)	Low (<100)	Low (<100)	Low (<100)
Special ecological areas lost (sq. km)	Low (<25)	Low (<25)	Low (<25)	Medium (25-100)
Valuesat risk				
People at risk/1,000	Medium (<10)	Medium (<10)	Medium (<10)	High (100-500)
Capital value at risk (% of nation's CV)	Low (<3%)	Low (<3%)	Low (<3%)	Low (<3%)
Other damages				
Agricultural land damaged by salinity (% of nation's total ag. land)	Low (<3%)	Low (<3%)	Low (<3%)	Low (<3%)
Response strategy implementation cost (% of nation's GDP; excludes annual costs)	Low (<1%)	Low (<1%)	Low (<1%)	Low (<1%)

ODRA ESTUARY

Under a 1.0-meter rise, some important polder areas and wetlands in the Odra Estuary would be inundated up to about 40 km upstream of Szczecin. Parts of the urban areas of Szczecin, Swinoujscie, and Police would also be inundated, including some ports and industrial sectors. For example, a 1.0-meter rise would endanger the chemical plant at Police.

COASTAL BARRIER LAKES

A chain of coastal barrier lakes lies from west to east along the mid-coast, ranging in size up to 71.4 km^2 (Lake Lebsko). The higher levels attained by storm surges in accelerated sea level rise scenarios would destroy dunes and would erode barrier islands and spits. This would lead to inlet breaches and sedimentation on the backside of barriers. Especially threatened are Lakes Jamno, Bukowo, and Kopan. An accelerated sea level rise might increase the area of the lakes, but this depends on whether other geological and biological processes adjust to the rate of the rise. The lakes would grow more saline as a result of more frequent inflows of Baltic waters through river mouths and through washing over barriers.

HEL PENINSULA

The Hel Peninsula is a unique formation separating the open sea from the Gulf of Gdansk. The peninsula is narrow (less than 300 meters) and vulnerable at the "base" segments close to the mainland, and expands to nearly 3 km at the head, Stary Hel. After many years of traditional protection by groins, light-weight revetments, tree planting, etc., the more modern technology of artificial beach nourishment has been applied since the mid-eighties, showing good prospects of erosion control.

GDYNIA AND GDANSK PORTS

Some port areas, urban districts, industrial areas, trade, and transportation routes of the Gdansk area are vulnerable to the impacts of accelerated sea level rise. Specifically, about 500 hectares of industrial area (ports included) and 680 hectares of urban area are threatened. The nearby port of Gdynia is less vulnerable than Gdansk (but not immune).

GDANSK METROPOLITAN AREA

Gdansk is a historic, business, and cultural center. The city's most historic buildings date from the 14th to 16th centuries. The reconstruction since the war has followed old plans and architectural styles. Some buildings and monuments have been placed in UNESCO's highest categories for historic preservation. Parts of the historic city areas are at risk of being flooded under a 1.0-meter rise if no protection is provided.

ZULAWY POLDER AREA AND WISLA RIVER

The Vistula Delta (Zulawy) is one of the most sensitive regions to the impacts of accelerated sea level rise. It is also among the most valuable. The gross agricultural area of the Zulawy polder district covers 180,000 hectares (2 percent of the land area of Poland). A large part of the area is situated below sea level. Large state farms cover about half of the area (between 500 and 8,000 hectares). The remainder is in private hands; these small farms each comprises an average of 6 hectares of land.

Extensive flooding during a gale in 1983 demonstrated the present vulnerability of the region and that flood protection should receive priority. However, roads, ditches, and drainage systems are in need of improvement and require regular maintenance. Many of the pumping stations are obsolete and need to be replaced. The rising sea water will enter rivers, navigation channels, and other waterways. At higher sea levels, storm barriers and gates are locked automatically in the Zulawy polder system. If the sea level is too high, the gates do not open, inland water accumulates upstream, increasing flooding dangers from the natural river and drainage flows. This mechanism is likely to be severe with a 1.0-meter rise in sea level.

The dikes built on the Zulawy polders are 2.2–2.3 meters high because Polish regulations require them to be 0.7 meters higher than the 50-year storm (i.e., an annual probability of 0.02), although the sea has risen 0.1 meters since some of them were built. The dikes already built will be too low for the conditions of accelerated sea level rise. The existing dikes are not designed to withstand high-water levels for longer than several days. In a saturated condition, they are subject to piping (migration of finer particles through layers of coarser grains of soil) and consequent loss of internal stability, causing sliding, settlement, and loss of cohesion. If the sea rises only 0.3 meters, then the dikes would be overtopped in a 50-year return-period storm. With a 1.0-meter rise, the dikes would probably be breached or overtopped.

SHORELINE RETREAT—ENTIRE COAST

The rate of erosion of Poland's 100 km of cliff coast has been well documented. It ranges from 0.36 meters/year at Trzesascz to 2.3 meters/year at Ustka. The dune retreat measured as the movement of the dune toe varies up to 2 meters/year on the Ustka coast to 3.3 meters/year in other places on the same coast One of the most disastrous of recent storms attacked the Polish coast on November 29, 1988. The water level recorded at Kolobrzeg was 0.75 meters above mean sea level, and wind gusts exceeded 20 meters/second. Although those conditions were very rare, they caused serious damage along the entire Polish coastline. Erosion at Mielno on November 30, 1988, following the storm, was recorded as being 4–60 meters^3.

For a design wave height of about 2.5 meters and an average bed slope slightly below 1 percent, the Bruun Rule yields an average retreat of 30–45 meters under a 0.3-meter rise and 100–150 meters under a 1.0-meter rise. Slightly modified by other computations and numerical modeling by the Institute of Hydro-Engineering in Gdansk, the rates of retreat were set at 50 meters for a 0.3-meter rise and 150 meters for a 1.0-meter rise over the next 100 years.

Increased sedimentation of the entrances to the harbors may be expected in Swinoujscie, Ustka, Darlowo, Kolobrzeg, and Wladyslawowo, as well as in the fairways leading to the harbors—e.g., the 30-km fairway in the Pomeranian Gulf leading to the harbors in Swinoujscie and Szczecin.

IMPACTS AND COSTS OF FULL PROTECTION

The "full protection" response strategy is defined for this study as implementing all feasible measures to minimize losses of any coastal land or values and to preserve the present status of the study area. Table 11 shows the property and land losses expected under a full protection strategy. This implementation cost of full protection would be about half the present capital value of what would be lost under a 0.3-meter rise. However, for the 30-year scenario, the shift in land uses and capital values would boost the capital value losses to over three times the full protection costs.

TABLE 11. VULNERABILITY ASSESSMENT: RESPONSE STRATEGY "FULL PROTECTION"

Impacts	**No Development**		**30-Year Development**	
	0.3 m	*1.0 m*	*0.3 m*	*1.0 m*
Values at Loss				
Capital value lost (% of nation's GDP)	Low (<1%)	Low (<1%)	Low (<1%)	Low (<1%)
Capital value lost (% of nation's CV)	Low (<3%)	Low (<3%)	Low (<3%)	Low (<3%)
People to be evacuated (x1000)	Low (<1)	Low (<1)	Low (<1)	Medium (1-50)
Ecological areas lost (sq. km)	Low (<100)	Low (<100)	Low (<100)	Low (<100)
Special ecological areas lost (sq. km)	Low (<25)	Low (<25)	Low (<25)	Medium (25-100)
Values at risk				
People at risk/1,000	Medium (<10)	Medium (<10)	Medium (<10)	Medium (<10)
Capital value at risk (% of nation's CV)	Low (<3%)	Low (<3%)	Low (<3%)	Low (<3%)
Other damages				
Agricultural land damaged by salinity (% of nation's total ag. land)	Low (<3%)	Low (<3%)	Low (<3%)	Low (<3%)
Response strategy implementation cost (% of nation's GDP; excludes annual costs)	Low (<1%)	Medium (1-3%)	Medium (1-3%)	High (3-10%)

The protection options considered include a variety of possible coastal defense measures, such as building and upgrading structures, nourishing beaches, increasing pumping, and elevating or abandoning land. In some cases, a setback line involving abandonment of some land or property is the only feasible course of action for protection of the hinterland (e.g., low-value agricultural land, wetlands).

Table 12 distinguishes between annual costs and "initial" (or capital) costs. The latter comprise beach nourishment costs and an annual maintenance cost. About 2 percent of the initial construction cost can be significant, bringing the capital costs over 100 years to three times the initial capital costs. This calls for replacing some structures within the 100-year period. The derived unit costs were multiplied to achieve the totals, which should be considered indicative because of the assumptions and grouping of structural types. Establishing a firm costing per structure for the present and in 30 years will require additional work in a future study phase.

TABLE 12. SUMMARY OF IMPLEMENTATION COSTS
FULL PROTECTION: WHOLE COAST

Response Strategies	**Sq. km**		**Zlx10^{9}/sq. km**		**Klx10^{12}**	
	0.3 m	*1.0 m*	*0.3 m*	*1.0 m*	*0.3 m*	*1.0 m*
			No Development (1992)			
Summary of initial costs						
Elevation of land	4.00	8.50	50.00	100.0	0.20	0.85
New polders	0.00	200.0	10.00	10.00	0.00	2.00
Additional pumping					0.17	0.87
Adaptation costs					0.13	1.30
Sea defenses					4.89	8.63
Adaptation of city fronts & wharves					0.24	0.99
Total initial costs					**5.63**	**14.64**
Summary of annual costs						
Beach nourishment					0.02	0.12
Maintenance costs 2% of initial costs					0.11	0.29
Total annual costs					**0.13**	**0.41**
Summary of losses						
Abandoned land	57.00	177.00	20.00	20.00	1.14	3.54
			30-Year Development (2022)			
Summary of initial costs						
Elevation of land	4.00	8.50	125.00	250.00	0.50	2.13
New polders	0.00	200.0	25.00	25.00	0.00	5.00
Additional pumping					0.43	2.17
Adaptation costs					0.33	3.30
Sea defenses					20.10	59.71
Adaptation of city fronts & wharves					0.60	2.48
Total initial costs					**21.96**	**74.79**
Summary of annual costs						
Beach nourishment					0.02	0.14
Maintenance costs 2% of initial costs					0.44	1.50
Total annual costs					**0.46**	**1.64**
Summary of losses						
Abandoned land	57.00	177.00	70.00	70.00	3.99	12.39

Elevation of Land and New Polders

Where constructing dikes or other defenses is not practical, land would be elevated, mostly in Area 2, along the low-lying coastal lakes. Some polder systems must be redesigned (mainly in the Odra River) by raising the dikes, adding new pump stations, increasing the rate of pumping, and other measures.

Additional Pumping

From a first analysis of increased seepage, drainage, pumping energy, and costs, it follows that the present polders would operate if pumping were increased by 10 and 50 percent under the 0..3- and 1.0-meter scenarios, respectively. The cost of additional pumping for the existing polders was calculated by multiplying the present area by 0.1 or 0.5 times the pumping cost per hectare (at the present cost or the projected 30-year cost).

Adaptation Costs

These include rough estimates for additional adaptation of some infrastructure items associated with full protection. Some harbor equipment and facilities would require upgrading, as would minor roads and services.

Abandonment of Land

A small area of land would be abandoned, mostly in Area 1 in the west. This has been entered in Tables 9–11 as the only "loss" encountered in the full protection strategy.

RECOMMENDED RESPONSES

The vulnerability analysis shows clearly that property and land losses, as well as the required relocation of people, would reach critical levels in the case of a 1.0-meter sea level rise over the next century. If delayed for 30 years, protection costs would increase from moderate to high levels. In the 30-year scenario, the increase in costs of protective measures for the 0.3- and 1.0-meter scenarios represents a major raising of the coastal structures to levels similar to those used in The Netherlands. This increment in cost is outweighed 10 times by the increase in capital values lost without protection. This justifies a review and possible implementation of higher dike and coastal structure crest levels and designs in the case of a 1.0-meter rise, affording a generally higher degree of protection and lower risk of failure.

Thus, the analysis shows the importance of acting sooner rather than later. However, it also emphasizes the importance of early warnings and reliable estimates of the expected rate of sea level rise. This will clearly assist managers and decision makers concerned with implementation of protection measures.

VULNERABLE SYSTEMS AND ECONOMIC SECTORS

Areas 1 and 4 would suffer the greatest damage in the event of accelerated sea level rise, along with the highest protection costs. The highest priority for protection would probably be the city and harbor areas of Gdansk, Gdynia, and the potential facility at Elblag; the urban/industrial area at Szczecin; and the polder system of the Zulawy Delta.

The loss of agricultural land in the Zulawy would be a serious blow to the regional economy, but the blow would be softened by Poland's huge and diverse national agricultural economy. Of serious concern locally and nationally would be the loss of urban or industrial land at Gdansk and Szczecin. Loss of ports would seriously affect trade and would be very costly. Thus, these areas would need to receive priority.

ODRA ESTUARY

Full protection of the Odra Estuary would require attending to the polders on the peripheries of the estuary. All existing polder dikes must be upgraded, and many new ones must be constructed. The retention polders near Szczecin need to be raised. The undeveloped wetlands within the Odra Estuary will be abandoned. Two kilometers of bay shores at Trzebiez should be protected by artificial beach nourishment.

COASTAL BARRIER LAKES

Full protection of coastal lakes has been assumed for costing purposes. The construction of new or upgraded dikes around lakes should be connected with an adequate protection strategy on the seaward side. In reality, a protection strategy would need to be carefully planned for assessing the least environmental damage to the coastal lake ecology.

SLOWINSKI NATIONAL PARK LAKES AND LEBA DUNES

Full protection in this case would rely on raised dikes surrounding the seawater areas, and increased pumping behind them.

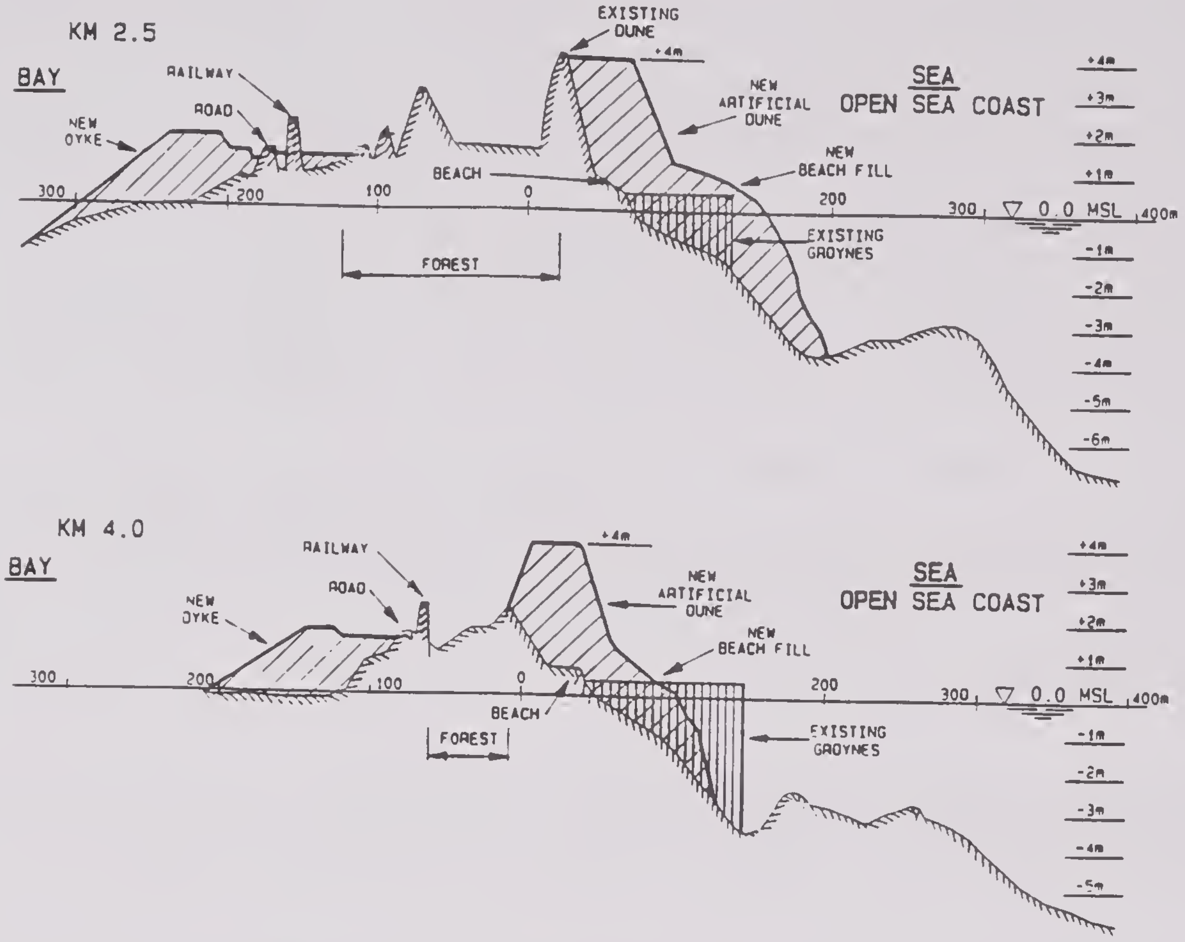
HEL PENINSULA

In accordance with the viewpoint of the recent Polish-Dutch Workshop (1991), beach nourishment is the preferred solution. The most feasible solution economically with respect to beach nourishment is pumping the sand ashore directly from the sea. (See Figure 5.)

CLIFF COASTS

The cliff coast of Jastrzebia Gora (near Rozowie) is morphologically unstable. A combination of beach nourishment, stabilization of the cliff, and toe protection measures is proposed in this case.

FIGURE 5. ADAPTATION OF THE HEL PENINSULA



GDANSK, GDYNIA, AND SZCZECIN PORTS

The most feasible solution accepted within this study consists of raising the endangered ports and facilities, or at least port wharves. Gdansk Northern Harbor would require extensive upgrading of various facilities and infrastructure.

GDANSK CITY AREA

The protection system envisaged would incorporate a combination of raising dikes and wharves, installing flood gates, diverting canals, and increasing pumping.

ZULAWY POLDER AREA AND VISTULA RIVER

Full protection of the Zulawy polders against a 1.0-meter rise would require a bulk adaptation of the existing dikes and the construction of some new dikes and storm- and flood-prevention facilities. Under a 1.0-meter rise, construction of 52 km of new dikes and adaptation of 647 km would be required. The storm barrier at the entrance of the Tuga River should be redesigned for a 1.0-meter rise, and other river gates must be considered to keep storm surges away from the delta. The number and capacity of pumping stations in the polders must be increased substantially.

INSTITUTIONAL AND PLANNING RESPONSES

Coastal management, planning, and implementation still need reorganization and improvement and should receive priority. According to the existing law, protection of the sea coast and of the coasts of the "internal sea waters" is the responsibility of the Maritime Offices in Szczecin, Slupsk, and Gdynia. However, permits for activities not classed as coastal protection activities are issued not by the Maritime Offices, but by other local or governmental authorities. The Maritime Offices have relatively little influence over these decisions. This situation resulted in poor coastal planning. Many costly—even disastrous—decisions concerning the use of coastal land and developments have been made against the judgment of the marine administration. On July 1, 1991, a new Act of Parliament, "On the Sea Areas of Poland and on Marine Administration," rectified this problem to a large extent. Awareness of the dangers from future rise in sea level is still low, both among the public and within the administrative units.

The processes already started by the rising sea will require town planners, designers, planning offices, economists, engineers, and decision makers to adopt a totally different approach and philosophy that will accommodate the analysis of the costs, risks, and effects of sea level rise.

PROPOSED STUDIES

Various studies are necessary to expand the data on the impacts of accelerated sea level rise. Toward that end, contacts and cooperation among institutions involved in coastal management and studies (planning, execution, research, education) should be strengthened.

- Additional vulnerability assessments should include a more detailed investigation of flooding scenarios, more study to investigate salinity impacts on the water supply of cities, more detailed examination of joint probabilities (wave height, surge, river flood), and more detailed studies and cost assessments of protection options.

- Decisions on protecting a specific area should be based on a more thorough analysis of the costs and benefits of these decisions. This analysis would include the vital vulnerable elements of the coastal zone. Also, by establishing good zoning regulations (for example, by requiring new buildings to be at least 150 meters from the cliff edge), future problems can be avoided without excessive protection costs and new construction. So, studies to address this policy issue are also highly recommended.

- The development of a coastal zone monitoring system and data bank is of crucial importance. The system should include annual measurements of the main parameters of the coastal zone along profiles set 1 to 2 km apart along the entire Polish coastline. The monitoring system and data bank should be operated by the proposed Advisory Branch of the Polish Ministry of Transport and Maritime Economy. The collected data and programs developed for data processing and analysis should be oriented toward the decision-making and design processes. However, they should also be useful to broadly support coastal zone research.

  Relatively short-term monitoring of development of such coastal protection projects as the beach nourishment on Hel Peninsula or by-pass system operation is also necessary. Information from these and other monitoring systems should be easily accessible to all institutions.

- The economic and environmental impacts of accelerated sea level rise on Poland need to be updated and explored in more detail, especially for the most vulnerable areas.

Remote sensing and GIS techniques have proven to be efficient and useful for these studies, and should be used for future studies.

- Efficient ways for implementing more integral coastal zone management and defense strategies.

- Technical assistance on the basis of knowledge exchange with respect to the items at stake, with special emphasis on coastal defense and maintenance, as well as environmental impact assessments.

FINANCIAL, LEGISLATIVE, AND ADMINISTRATIVE REQUIREMENTS

To achieve these goals, it is necessary that adequate logistics, funding, and other support from Poland and abroad can and will be arranged.

- Institutions concerned with the impacts of accelerated sea level rise should jointly formulate legal and administrative requirements for adequate coastal management (routine monitoring, interactions, etc.). This would include setting safety standards and determining the so-called technical belt along the Polish coastline.

- Funding of both research and implementation of response strategies on the Polish coast is a decisive factor of success. This requires priority.

CONSTRAINTS TO IMPLEMENTING THE RECOMMENDED RESPONSES

Table 13 summarizes the factors affecting the feasibility of the response strategies. The critical components of constraint are economic and institutional. At present, the economy cannot support the costs of full protection.

Clearly, the challenge facing Poland and assisting nations is to allocate scarce financial resources in a timely and appropriate manner based on clear cost-benefit analyses. Raising awareness of the need for protective measures against sea level rise in an economy facing many other socioeconomic pressures will be critical to success.

Further, the Polish structure, interaction, and regulation governing coastal zone management planning pose a critical constraint. Developing an effective, integrated coastal zone management plan, including appropriate legislation and authority, will be essential to ensure that all protective measures taken in the coastal zone against sea level rise (and all other developments) are carefully planned.

In Poland, education and technical competence are superior. Therefore, these factors present no constraints to implementation.

TABLE 13. FACTORS AFFECTING IMPLEMENTATION FEASIBILITY

Implementation Factors (Degree of importance to implementation)	**Problem**	**Partial Problem**	**No Problem**
Legislative/Institutional/Organizational (Critical)			
Institutional constraints			
Existing legislation re CZMP		x	
Existing institutions/organizations in CZMP	x		
Executive powers for CZMP	x		
Operational constraints			
Specification of tasks & responsibilities		x	
Communication structure		x	
Staffing and facilities			x
Existing CZMP plan, regulations, control, etc.	x		
Quality constraints (effectiveness)			
Staff education level			x
Knowledge & management capabilities			x
Staff motivation & working conditions			x
Economic & Financial (Critical)			
Institutional constraints			
National economic bearing capacity (1.0 Full Protection)	x		
Operational constraints			
National/regional funding potential	x		x
International funding potential		x	
Quality constraints (effectiveness)			
Financial management capability			x
Technical (Moderate)			
Institutional constraints			
Technical knowledge & experience			x
Technical institutions			x
Operational constraints			
Operational structures			x
Staffing and facilities			x
Quality constraints (effectiveness)			
Staff education level			x
Technical qualification/capability			x
Staff motivation			x
Data availability		x	
Cultural & Social (High)			
Institutional constraints			
Cultural constraints			x
Socioeconomic constraints	x		
Operational constraints			
Cultural programs			x
Socioeconomic programs		x	
Quality constraints (effectiveness)			
Recent cultural achievements			x
Recent socioeconomic achievements		x	

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THE IMPACTS OF SEA LEVEL RISE ON THE COASTLINE OF SENEGAL

Isabelle Niang
Dept. De Geologie
Universite C.A. DIOP
Dakar-Fann, Senegal

Karen Clemens Dennis and Robert J. Nicholls
Laboratory for Coastal Research
University of Maryland
College Park, Maryland

ABSTRACT

Two-thirds of Senegal's population (4.5 million people) and 90 percent of its industry (including its entire tourist industry) are concentrated in the coastal zone, mainly along 68 km of the country's 500 km of open ocean coastline. A 1-meter rise in sea level would permanently flood over 6,000 km^2 of land, most of which is wetlands. However, erosion would cause the biggest problem, threatening structures valued at $499–707 million (or 12–17 percent of Senegal's 1990 GNP) and displacing 110,000 –180,000 people.

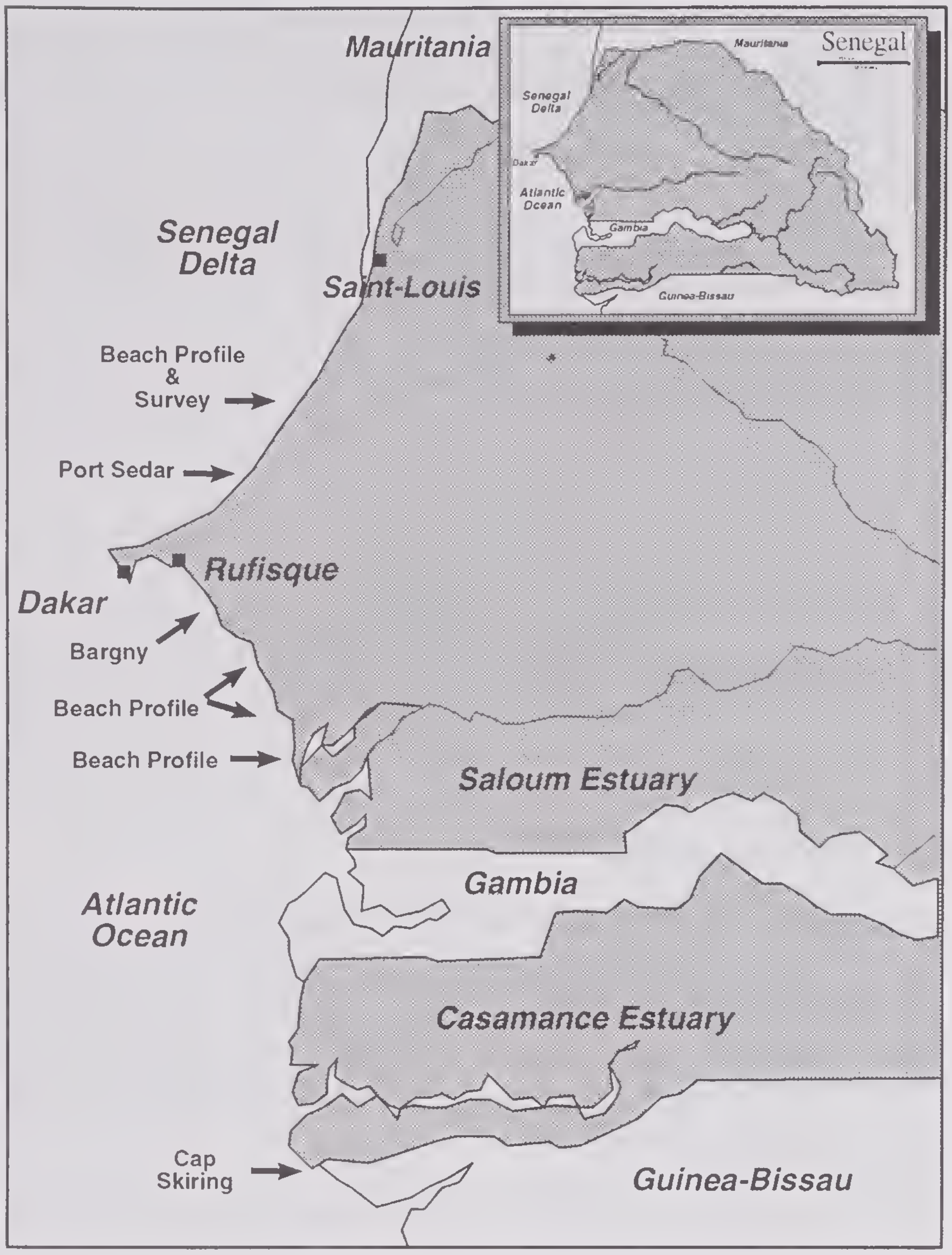
Protecting the developed areas would cost $255–845 million, most of which would go toward beach nourishment. Assuming that this investment occurred over 50 years (2050–2100), it would represent an annual cost of 0.9–3.0 percent of the national gross investment (1987 value). Adaptive responses to minimize the country's vulnerability to sea level rise include requiring building setbacks for future tourist developments and encouraging development within the hinterland, away from the coastal zone.

BACKGROUND

Senegal's 2,065-km coast comprises long stretches of sandy coastline facing the Atlantic Ocean, the Senegal Delta (at Saint Louis), the sheltered shorelines of the Saloum and Casamance estuaries, and a small length of rocky shoreline (see Figure 1). About 4.5 million people (two-thirds of the population) live in the coastal zone (Niang, 1990). The metropolitan area around the capital Dakar (greater Dakar) alone contains 2 million inhabitants and 90 percent of the country's industry. The Intergovernmental Panel on Climate Change ranked Senegal as the 45th most vulnerable country in the world to sea level rise, in terms of annual protection costs (IPCC, 1990). A preliminary study of Senegal has demonstrated that sea level rise would have major impacts (Niang, 1990). It would primarily cause inundation in the delta and estuaries and erosion along the sandy coastlines.

While Dakar itself would not be affected by inundation or erosion, as it is situated on a rocky headland, much of greater Dakar is low-lying. In addition, the aquifer supplying water to Dakar and the surrounding areas could be affected by saltwater intrusion and other impacts of climate change. Operation of the important harbor at Dakar could be impeded, and the important tourist industry could suffer a serious setback due to erosion causing damage and loss of structures.

FIGURE 1. THE COASTLINE OF SENEGAL



COASTAL CHARACTERISTICS

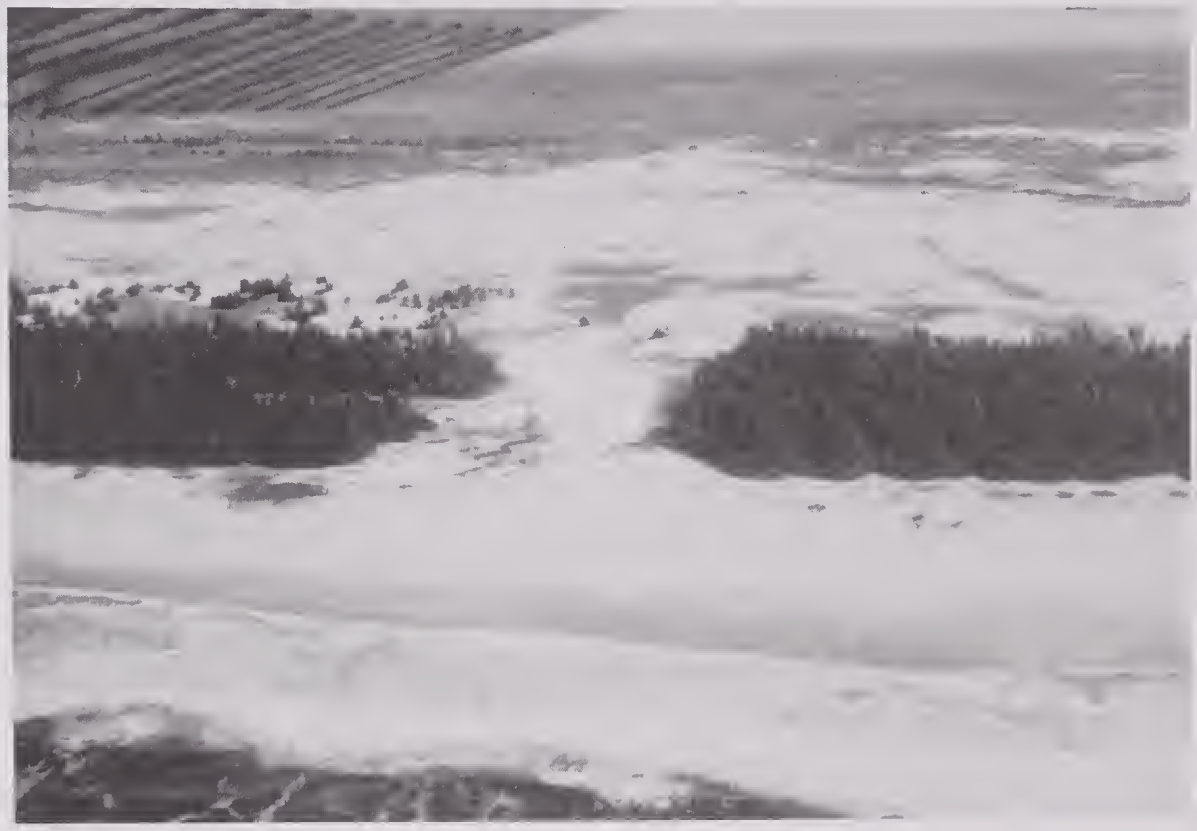
The Senegal Delta is located along the Senegal River on the northern border with Mauritania. The delta area is used extensively for agriculture, particularly rice and sugarcane.

In the late 1980's, the Diama dam was built to control saltwater intrusion into the river. However, because sea level rise was not considered in the design, the Senegal Delta could become vulnerable to increased saltwater intrusion. In addition, the Diama and other upstream dams have greatly reduced sediment supply to the delta (Michel and Sall, 1984; Niang, 1990). Therefore, relative sea level rise may be substantially higher in the delta (Milliman et al., 1989), and the shoreline along the open coast is expected to recede.

The sandy coast of Senegal can be divided at Dakar into a high-wave-energy northern coast (La Grande Cote) and a lower-wave-energy coast to the south (La Petite Cote). For the purposes of this study, La Petite Cote is considered to extend to Guinea-Bissau.

The north coast receives a persistent southwesterly swell from the north Atlantic and has a wide surf zone and large littoral drift (Guilcher, 1985). Several lines of sand dunes run along the coast. Interdune slacks, termed *niayes* allow the water table to reach the surface and are used for vegetable production. The Grande Cote is relatively undeveloped, with a low population and few towns. Migratory fishermen inhabit a number of villages, comprised primarily of temporary structures. The high wave energy has made the north coast unsuitable for tourist development. A notable feature of this coast is a linear strip of reforestation on top of the first dune, several hundred meters wide, which extends the entire length of the coast (over 100 km) (Figure 2). Thus, while sea level rise will cause erosion, the impacts on the local population are expected to be relatively limited and localized.

FIGURE 2. REFORESTATION ALONG THE GRANDE COTE



In contrast, the Petite Cote is comprised of a number of developed coastal towns, most significantly the area of greater Dakar between Dakar and Rufisque on the south of the Cap Vert Peninsula. Dakar itself is situated on a rocky headland, but much of the surrounding metropolitan area is "at risk" to sea level rise. The wave conditions are less severe, and tourism is a growing industry. Many of these tourist villages, including the area south of the Casamance estuary, have been constructed close to the water's edge (Figure 3). These facilities and the money they generate for the Senegalese economy would be destroyed by relatively small amounts of beach erosion. Thus, the south coast appears to be vulnerable to sea level rise.

The Casamance and Saloum estuaries are situated south of Dakar. They contain large and important areas of marshes and mangroves (Guilcher, 1985), along with farmland, whose principal product is rice. The lower rainfall of the last few years has increased salinization in the estuaries, killing the marshes and mangroves. Cutting of the mangroves to provide land for rice culture has also greatly reduced the mangroves. Areas devoid of plants for these reasons are termed *tannes*.

FIGURE 3. A COASTAL TOURIST RESORT

ANALYTICAL METHODS

This study focused on two major consequences of sea level rise: (1) land and associated economic losses, and (2) the cost of various protection options. It assumed existing population levels and existing distribution of coastal development. Ranges reflect uncertainties about the magnitude of erosion.

SEA LEVEL RISE SCENARIOS

The study used four arbitrary scenarios of eustatic (or worldwide) sea level rise: 0.2 (no acceleration), 0.5, 1.0, and 2.0 meters by the year 2100. Douglas (1991), who has presented the most comprehensive and rigorous analysis to date, estimated the worldwide rise in sea level over the last century to be 1.8 mm/yr. We used Douglas's value as our baseline (or no acceleration) scenario, giving a 0.2-meter rise in sea level by the year 2100.

These eustatic scenarios need to be converted into relative (or local) sea level rise scenarios. Relative sea level rise is a combination of eustatic changes and any uplift/subsidence of the land. The best (and only) sea level data for Senegal are at Dakar for the years 1943 to 1965 (with gaps). This data show no statistically significant change in sea level, although a best fit shows an upward trend of 1.4 mm/yr. This is similar to the results of Elouard et al. (1977) and similar to the worldwide eustatic sea level trend of Douglas (1991). Long-term geologic data from the Senegal Delta also suggest that subsidence is very low (<0.2 mm/yr) (Faure et al., 1980). Therefore, for all practical purposes, the eustatic scenarios can be applied directly as relative sea level rise scenarios.

AERIAL VIDEOTAPE-ASSISTED VULNERABILITY ANALYSIS

One of the major problems with studying the impacts of sea level rise in developing countries is the lack of detailed information on coastal geomorphology and the existing pattern and scale of development. Most fundamentally, coastal elevations are poorly known (IPCC, 1990). While the best topographic maps of Senegal had 5-meter contours, these only have very local coverage (the Cap Vert Peninsula). Most maps have a 40-meter contour interval, which is of limited value when analyzing land loss for any reasonable sea level rise scenario.

We examined several methods of obtaining the topographic data we required, including aerial photography and satellite imagery. Both methods are prohibitively expensive and time consuming. In the case of satellite imagery, even in the most ideal conditions, a 20-meter contour is the highest accuracy possible (Theodossiou and Dowman, 1990). This is clearly inappropriate for our purposes.

Given these constraints, our strategy was to characterize the coastal development and geomorphology, including roughly estimating coastal elevations by obliquely videotaping the coastline at low elevation (50 to 100 meters) from a small airplane (Figure 4) (Nicholls et al., 1992; Nicholls et al., in press; and Dennis et al., 1991). We analyzed this information in conjunction with existing and limited new ground-truth information to determine the physical and, hence, economic impacts of sea level rise. Before the flight, we divided the Senegal coast into a working geomorphic classification using published information and expert knowledge, and obtained the best maps. We then videotaped the coastline, including the Casamance and Saloum estuaries, at low and high altitudes (76 meters and 300 meters, respectively). We were unable to fly the Senegal Delta because of flight restrictions. A recorded commentary throughout the flight greatly enhanced the value of the video record, which provided the following information on the coastline:

- *Index of terrain and relief changes.* We have a cross-sectional view along the coastline which enables us to estimate the relative topography of the coast at the shoreline. Any major cartographic errors are also apparent.

- *Types of coastal environments.* We can identify the location and size of marshes, mangrove swamps, sandy beaches, and dunes, etc. This is very useful for determining if erosion or inundation will be more prevalent.

- *Land-use practices.* This helped us to determine how coastal lands are used (e.g., agricultural, urban).

- *Infrastructure.* We now have a detailed record of the infrastructure that will be affected by sea level rise.

- *Population.* The video provides quantitative indicators of the population living in the coastal zone and whether it will be directly affected by sea level rise.

The most important limitation of this method is that, unlike traditional procedures involving aerial photographs, parallax is not used to estimate elevations. Instead, researchers use the video record to classify the coastal land forms and subjectively interpolate elevations between occasional ground-truth data (either reliable spot heights or surveyed transects). Clearly, this procedure would not provide an accurate contour for anyone who needed to know whether a particular parcel of land would be inundated. However, validation experiments in Maryland's Chesapeake Bay have demonstrated that this method is unbiased and reasonably accurate when estimating land loss on a large scale.

FIGURE 4. THE AIRPLANE USED FOR THE AERIAL VIDEOTAPE-ASSISTED VULNERABILITY ANALYSIS

This technique is especially attractive because it allows for surveying large expanses of coastline quickly with a limited budget. A similar procedure is already used in Louisiana, where the coastal zone is retreating so rapidly that a quick and inexpensive method for determining coastal geomorphology is essential (Byrnes et al., 1990; Debusschere et al., 1991). The flexibility of the method allows rapid mobilization, for instance, after the passage of a hurricane.

FIELDWORK

After the videotaping, we made ground trips to as many representative coastal types as possible. We recorded topographic information along the areas indicated by arrows in Figure 1, together with information concerning land and property values, agriculture, future plans for development, etc. We were unable to travel south of The Gambia because of logistical difficulties.

LAND LOSS ESTIMATES

EROSION

The Bruun Rule is a frequently used model for calculating erosion due to sea level rise (Bruun, 1962; Hands, 1983; Leatherman, 1991). It predicts that a low-gradient beach will have a greater retreat for a given rise of sea level than a steep beach (Figure 5). We used the following form, after Hands (1983):

$R=G^*S^*(L/(B+h_*))$

where:

R is the shoreline recession due to a sea level rise S;

h_* is the depth of closure;

B is the dune height (note $H = h_* + B$ - Figure 5);

L is the active profile width from the dune to the depth of closure (Figure 5);

G is an overfill ratio.

These parameters were estimated from field data and available charts. G was assumed to be unity (all eroded material is sand), so these recession estimates are minimum values. The depth of closure is the variable in the Bruun Rule that is the most difficult to estimate (Hands, 1983). In particular, the value will depend upon the time scale of interest: the longer the period under consideration, the larger the depth of closure (Stive et al., 1990). There are no accepted methods for estimating depth of closure over the long time scales of interest. Therefore, for our calculations we used low and high estimates of closure depth (d_{L1} and d_{L100}, respectively). We treated d_{L1} as the same definition as d_l of Hallermeier (1981), and we approximated d_{L100} by:

$$d_{L100} = 1.75^*d_{L1}$$

These depths are referenced to a datum 1 meter above low water.

Visual wave measurements are available from Bargny (Sogreah, 1981a) and from Port Sedar (Sogreah, 1981b) (Figure 1). The resulting depths of closure are given in Table 1. We used the Port Sedar value north of Dakar and the Bargny value south of Dakar. Recent profile measurements off Rufisque suggest that d_{L1} is about 4 meters, agreeing with our results.

TABLE 1. DEPTHS OF CLOSURE NORTH AND SOUTH OF DAKAR

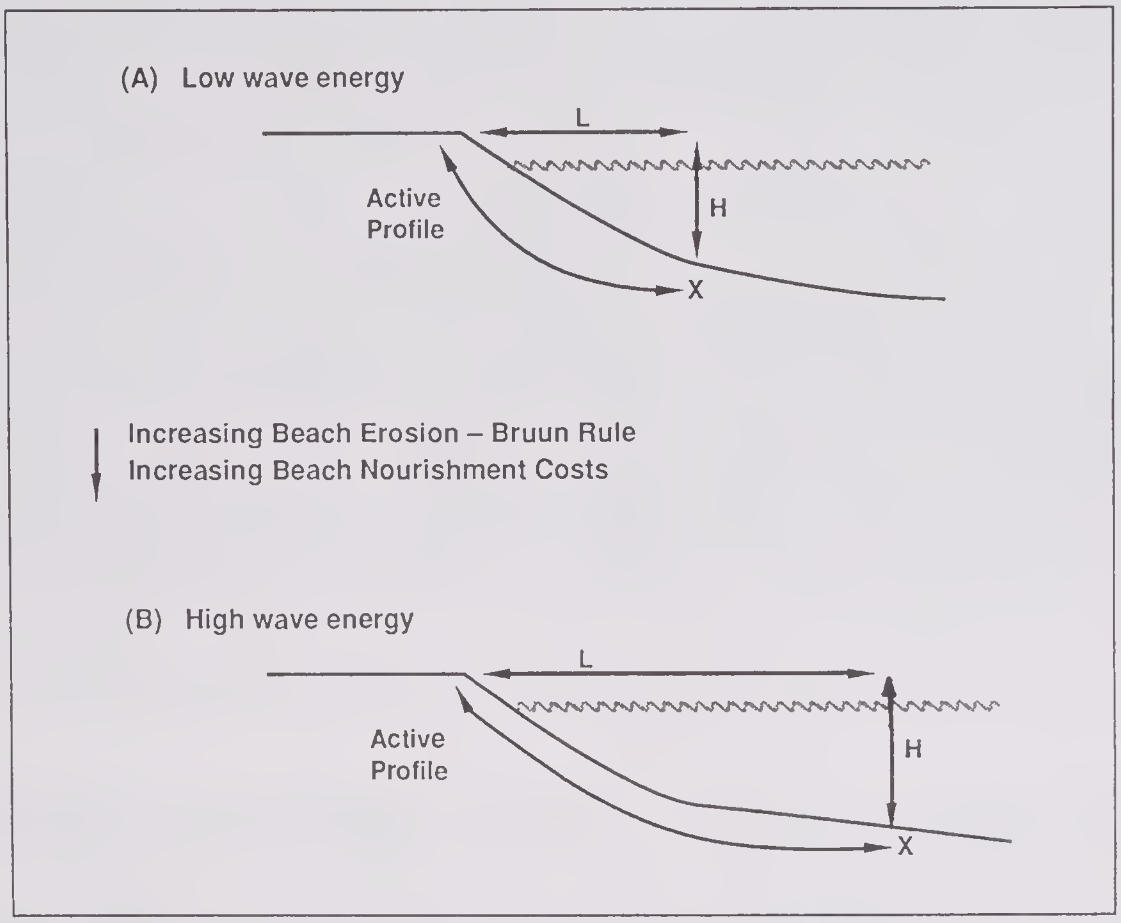
Coastal Area	D_{L1}	D_{L100}
North Senegal (Port Sedar)	6.3 m	11.0 m
South Senegal (Bargny)	3.4 m	5.9 m

The low and high active profile widths (corresponding to d_{L1} and d_{L100}, respectively) were determined at different locations along the coast using the best charts and linear interpolation. The low estimate ranged from 100 to 2,500 meters, while the high estimate ranged from 300 to 8,000 meters. The North Coast from Dakar to the Mauritanian border is uniform, so application of the Bruun Rule was straightforward. South of Dakar, the beach widths and dune heights are more variable. Therefore, we divided the coast into segments of equivalent beach width and dune heights, using the low video record together with surveyed beach profiles. Then we applied the Bruun Rule. An additional problem on the south coast is that the beaches are often backed by marshes and mangroves. We estimated land loss in these areas by using a combination of erosion (of the beach) and inundation of the wetlands.

INUNDATION

In the case of wetlands and other coastal lowland, we applied a direct inundation, or "drowning," concept. One- and two-meter contours (above high water), plus the area of existing mangroves, were estimated from a combination of the video record and available maps. Land loss due to lower scenarios was linearly interpolated from a 1-meter rise. Inundation is most significant in the Senegal Delta and the Saloum and Casamance estuaries (Figure 6). For these low-lying areas, the video record is insufficient to define an estimate of elevation, so it was integrated with available maps, plus expert judgment. This is not to undervalue the video record, as it provided a check on the validity of the maps and helped to define the present extent of mangroves. As already noted, we could not videotape the Senegal Delta, so our inundation estimates are based solely on available maps.

FIGURE 5. THE IMPORTANCE OF ACTIVE BEACH PROFILE WIDTH



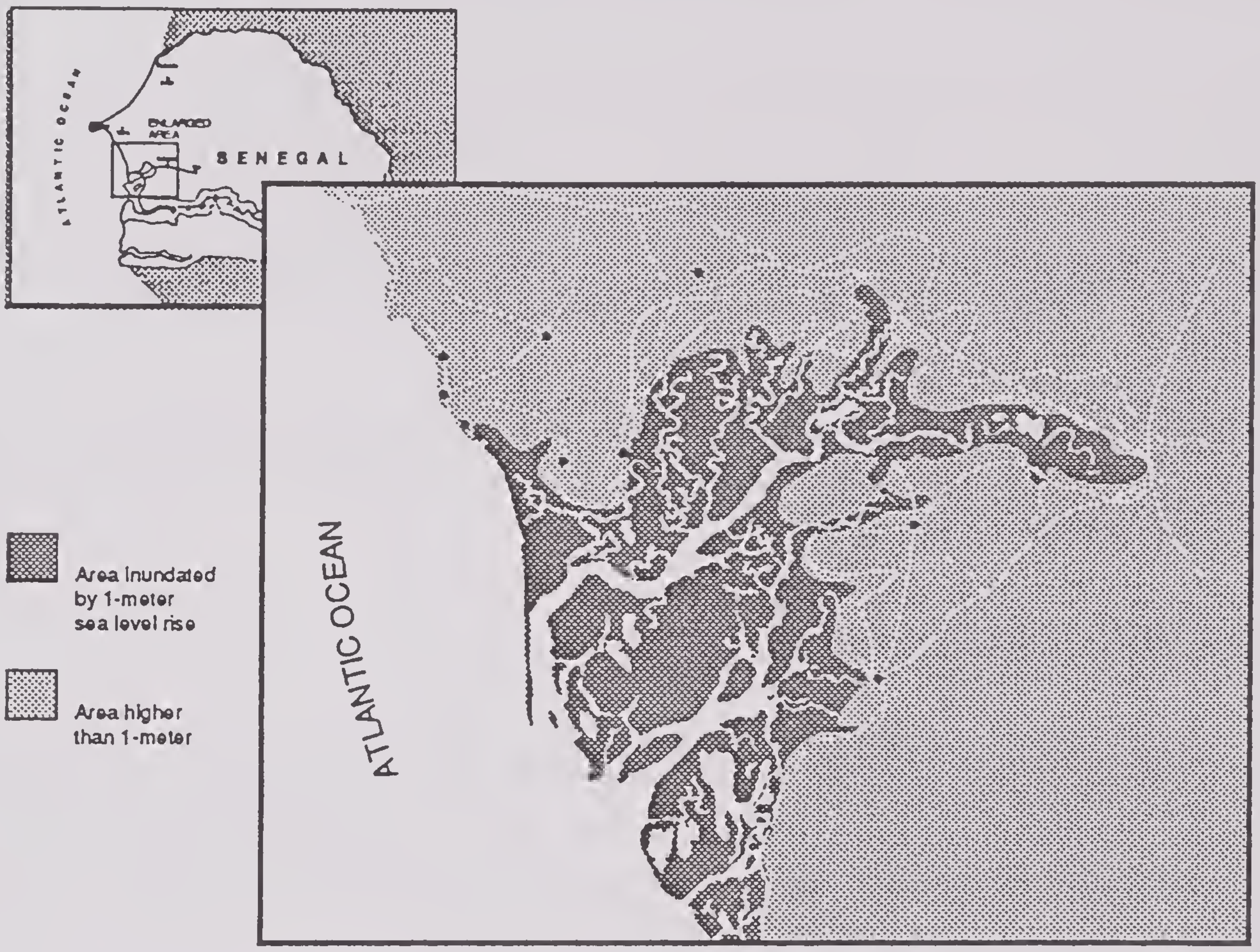
Most of the active beach profile is submerged, as illustrated. In areas with high wave energy, the active profile width is larger, all other factors being equal. This results in increased beach erosion and larger volumes of sand required for beach nourishment.

These calculations do not consider the possibility of sedimentation in the inundated area. Coastal marshes (Gehrels and Leatherman, 1989) and mangroves (Ellison and Stoddart, 1991) can accrete vertically in response to slow rates of sea level rise and are only inundated above a certain threshold value of sea level rise. Mangrove loss due to sea level rise is not reported to be a problem in Senegal at present. Therefore, we assumed that the threshold value of sea level rise, regarding inundation, is the present rate of rise: 0.2 meters by the year 2100. Thus, when the drowning concept was applied, the mangroves only experience inundation for scenarios greater than 0.2 meters. For the mangroves we assumed 50 percent loss for 0.5 meters and (effectively) 100 percent loss for scenarios of 1.0 meter and greater. Wetland migration was not evaluated.

ECONOMIC AND LAND-USE ANALYSIS

We then examined the impacts of land loss in terms of economic value and coastal resources and the different protection options. To supplement the data already collected, we estimated the distance that each developed coastal area extends and the percentage of structures and crop land in that area. The coastal areas that would be lost for each sea level rise scenario were then superimposed on these estimates to calculate losses. This allowed us to estimate the number and type of buildings and, in turn, the displaced population. The population estimate depends upon a number of assumptions, including family size and building use. We assumed that no population would be displaced from tourist areas.

FIGURE 6. ESTIMATED INUNDATION IN THE SALOUM ESTUARY DUE TO A 1-METER RISE IN SEA LEVEL



The resources and infrastructure "at risk" are valued using the best available in-country data. For structures, the sizes and values given in Table 2, which are based on in-country experience were utilized. Large areas of agricultural land will be lost due to sea level rise, but this is not presented here due to a lack of information concerning the total area and its value. Similarly, the role of wetlands in coastal resource availability could not be assessed, due to limited existing knowledge.

TABLE 2. SIZE AND VALUE OF STRUCTURES BASED ON IN-COUNTRY ESTIMATES (IN THOUSANDS OF 1990 U.S. DOLLARS)

Structure Type	**Size (m^2)**	**Value**
Fishing Village House	75	$15
Small House	100	30
Tourist House	200	60
Tourist Villa	800	200
Buildings		30 (/100m^2)
Factories		30 (/100m^2)
Tourist Hotels		60 (/100m^2)

ESTIMATED COSTS OF PROTECTION

Four protection options were considered as follows:

1. *No Protection.*

2. *Present Protection* .Existing protection, including harbors, is maintained. We did not have the information to calculate the costs for harbors, so we used the costs given by IPCC (1990).

3. *Important Areas Protection.* Medium to highly developed areas, plus strategic areas (as assessed by the videotape and other sources), are protected (e.g., cities, tourist beaches, factories). Using the video record, we defined medium to high development as areas with more than 15 percent of the ground covered with structures. For tourist areas, we assumed beach nourishment. Elsewhere, sea walls are used since beach loss is not a primary consideration. Where appropriate, relocation is suggested as an option.

4. *Total Protection.* All coastal areas with a population greater than 10 people/km^2 are protected (IPCC, 1990). We assumed that all protection additional to Important Areas Protection would be sea walls.

NOURISHMENT AND SEA WALL DESIGNS

The protection options were developed as follows using in-country costs, where possible. For sea walls and groins, we used the costs of purchasing, transporting, and placing rock (\$75/m^3), plus design costs (10 percent) and maintenance costs (20 percent), to determine a total cost. The cost of beach fill (sand) was estimated to be U.S. \$6/m^3 (DHV, 1979). No protection costs were determined for baseline conditions (a 0.2-meter rise).

Beach Nourishment

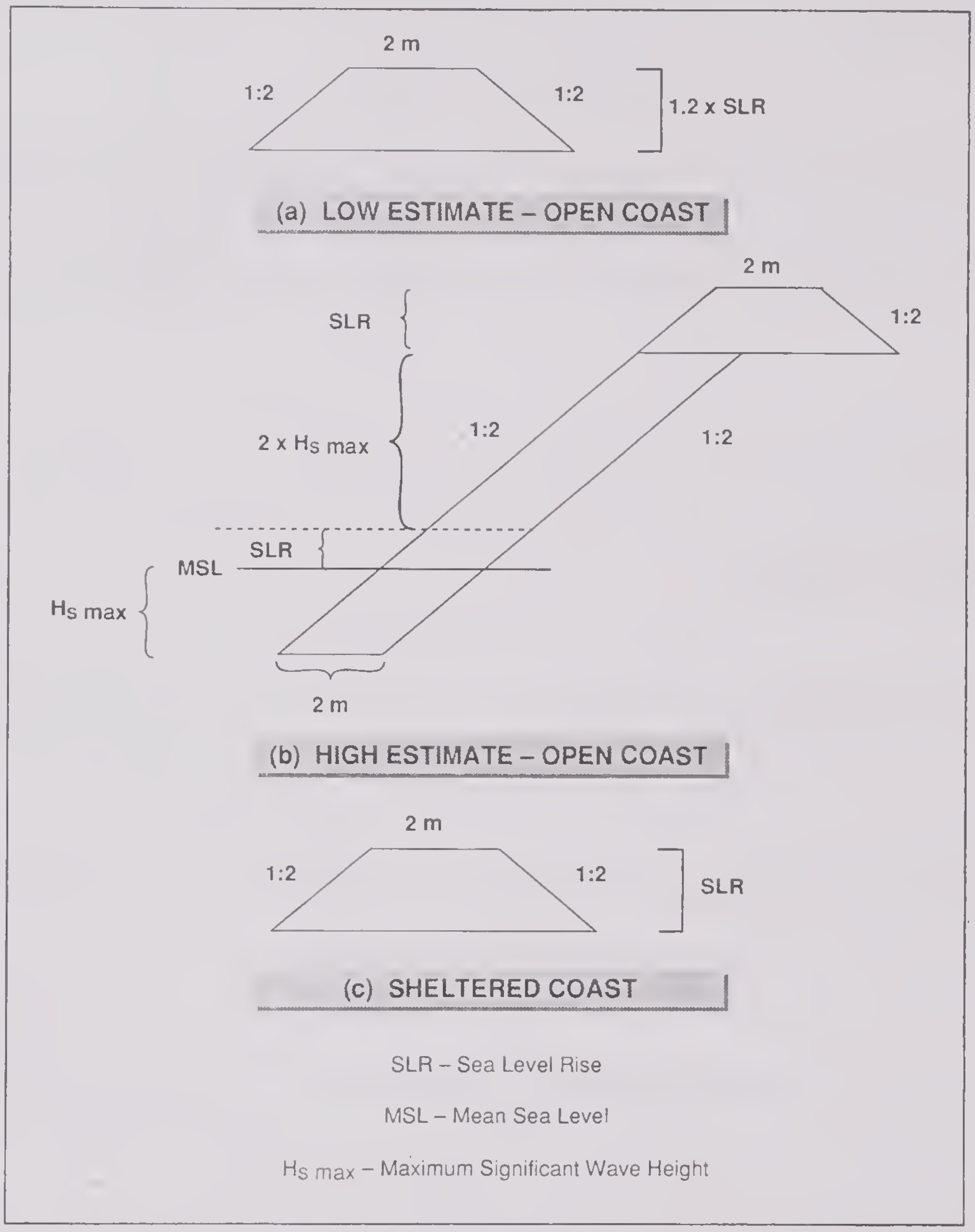
The volume of beach fill was calculated by raising the entire active profile by the sea level scenario. However, as with the Bruun Rule calculations, the active width is difficult to determine (Stive et al., 1991). In our case it is logical to use the low and high active widths already defined for the Bruun Rule as low- and high-cost designs, respectively.

An additional cost on long, open beaches is longshore loss of sand out of the nourished area (Dean, 1983). To stop such losses we propose large terminal groins at the ends of each nourishment project which, in effect, convert the open beach into a pocket beach. The terminal groins extend from the dune to the seaward limit of the profile, which can be several kilometers offshore. While this procedure raises the costs of beach nourishment significantly, the resulting costs are more realistic than simply considering the cost of a single beach fill (Titus et al., 1991). From an environmental perspective, renourishment may be preferred, but the costs will again be much greater than a single beach fill (Davison et al., 1992).

Sea Walls

To calculate the cost of erecting a sea wall, we developed three simple sea wall designs, whose application depends on wave environment. These are a low- and a high-cost sea wall for open (or wave-exposed) coasts (LCOC and HCOC) and a sea wall for sheltered coasts (SC). They all use 1:2 slopes and a 2-meter berm (Figure 7).

FIGURE 7. SEA WALL DESIGNS



The LCOC and HCOC designs are necessary due to the uncertain response of the beach to sea level rise. In the best case (lowest cost), the beach would not erode at all, while in the worst case (highest cost), the beach would be completely lost. Actual behavior will lie somewhere in between these extremes, with total beach loss more likely with higher sea level rise scenarios. The LCOC design assumes no beach erosion and only considers the effects of a more severe nearshore wave climate. The HCOC design assumes total beach loss and, hence, the need to prevent undermining of the wall. The size and the cost of the HCOC design increase with wave climate. Thus, the LCOC and HCOC designs reflect the two cost extremes. The SC design is lower than the LCOC design, as the sheltered coast would have limited problems with a more severe nearshore wave climate. The unit costs of the different sea walls are given in Table 3. We assumed that the cost of upgrading existing sea walls would be the same as building a new sea wall.

TABLE 3. SEA WALL COST PER KILOMETER (MILLIONS OF 1990 U.S. DOLLARS)

Sea Wall Type	**Sea Level Rise** **0.5 m**	 **1.0 m**	 **2.0 m**
Sheltered Coast	$0.12	$0.33	$1.07
Low Cost Open Coast	0.16	0.44	1.35
High Cost Open Coast (North Senegal)	2.00	2.30	3.10
High Cost Open Coast (South Senegal)	1.40	1.70	2.60

The 1:2 slope was chosen instead of the 1:4 slope that is used for the cost estimates of IPCC (1990) since the 1:2 slope is more economical and is the standard in the United States. Using the IPCC 1:4 slope and a 4-meter berm width would double the cost of sea wall construction. However, the range of our costs for wave-exposed coasts embraces the IPCC costs due to our high-cost design.

RESULTS

ECONOMIC AND LAND LOSSES

Table 4 illustrates the amount of land lost from each erosion and inundation, plus total land loss. For the baseline scenario alone (0.2m), the predicted losses are significant. In general, inundation is responsible for more than 95 percent of the land loss, independent of the scenario considered. For the 1.0- and 2.0-meter scenarios, for example about 2,150 km^2 of mangroves would be inundated. However, erosion would have a larger human impact than inundation, despite its relatively small magnitude, because most of the cities, towns, and tourist areas are located on the sandy coastlines and many structures would be lost and damaged due to the loss of this land.

TABLE 4. ESTIMATED LAND LOSS FROM SEA LEVEL RISE (KM^2)

Effect	**Sea Level Rise** **0.2 m**	 **0.5 m**	 **1.0 m**	 **2.0 m**
Erosion	11-18	28-44	55-86	105-157
Inundation (Including Mangroves)	338	1,919	5,987	6,389
Total	**349-356**	**1,947-1,963**	**6,042-6,073**	**6,494-6,46**

NO PROTECTION CASE

In the No Protection case, all of the land listed in Table 4, and all structures, plus their estimated value would be lost (Table 5). For the 1-meter scenario, land loss includes about 6,000 km^2 and economic losses range from U.S. $500 to $707 million.

Most of the predicted damage and loss of structures occurs along the Petite Cote, from Dakar to the beginning of the Saloum estuary. This area is highly populated with towns, industry, and tourist resorts. The area with the highest concentration of towns and industry is the south coast of the Cap Vert Peninsula, which contains 26 km of highly developed coastline. The value of the structures lost just in this area, from a 1-meter sea level rise, is between U.S. $76 and $192 million, if no protection is provided.

TABLE 5. NO PROTECTION - RANGE OF VALUE LOST EXCLUDING HARBORS AND CROPLAND AND PEOPLE DISPLACED (MILLIONS OF 1990 U.S. DOLLARS AND 1990 GNP)

Rise (m)	Value	%GNP	People Displaced (thousands)	% 1990 Pop.
0.2	$142-228	4-6	30-55	0.4-0.7
0.5	345-464	9-11	68-103	0.9-1.3
1.0	499-707	12-17	109-178	1.4-2.3
2.0	752-1,101	19-27	188-305	2.4-3.9

The most southern section of coastline also includes much tourism, especially in the Cap Skiring area near the south border with the Guinea-Bissau. Sea level rise would cause shoreline recession in the tourist areas, along with damage to structures. Under the same scenario, 110,000 to 180,000 people (or 1.4 to 2.3 percent of the 1990 population) would be displaced (see Table 5). The large number of refugees could place strains on Senegalese society.

Most of the land lost from a 1-meter rise in sea level would be due to the inundation of the delta and estuaries. Although these areas are not very highly populated, they contain highly valuable agricultural land (rice, millet, and vegetables) and fisheries.

PRESENT PROTECTION

This option is little different than the No Protection option, as existing protection is so limited. It would reduce economic losses by 10 to 20 percent over no protection.

IMPORTANT AREAS PROTECTION

Under this option, most of the land (6035-6060 km^2 for the 1-meter scenario) would still be lost since the Important Areas Protection option only protects 65.5 km (Table 6) of Senegal's 500-km open-ocean coastline, and not the estuaries and delta. This option would protect all of the developed land and therefore, most of the economic value; but would not protect agricultural and uninhabited land along the sandy coastline and the mangroves, marshes, and agricultural land in the Delta and estuaries. We were unable to assign economic value to this land.

TOTAL PROTECTION

This option would fully protect dry land, including agricultural land. However, adjacent wetlands or mangrove swamps would be inundated and destroyed impacting fisheries and some agricultural areas. Land loss would still be high (5,987 km^2 for the 1-meter scenario), since the majority of the land lost due to accelerated sea level rise, is wetlands in the delta and estuaries.

TABLE 6. OPTIONS FOR PROTECTING IMPORTANT AREAS*

Development Type	Length (km)	Protection Option
Towns	34	Sea Wall
Industrial	3	Sea Wall
Towns With Sea Walls	7	Sea Wall Upgrade
Tourist Areas	21.5	Beach Nourishment
Fishing Villages	3	Relocation
Total	68.5	

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*Excludes Dakar Harbor.

OTHER POSSIBLE IMPACTS

Sea level rise would cause saltwater intrusion in Senegal's aquifers and surface waters. This would damage agricultural production in several areas, including the Senegal Delta. It would also damage vegetable gardening in the niayes.

Salt water may also contaminate the freshwater aquifer located under Dakar at the head of the Cap Vert Peninsula. While this was not considered quantitatively in this study, this could represent a major problem. This aquifer supplies, in part, the drinking water for the 2 million population of Greater Dakar. Presently the demand exceeds the natural recharge, and saltwater intrusion is already occurring. Demand is expected to increase as the population of Greater Dakar is expanding rapidly, due to high birth rates and immigration from the Sahel regions of Africa.

PROTECTION COSTS

Under all the protection options, large areas of wetlands would be lost, with uncertain environmental and coastal resource implications. Following are the costs of each protection option.

NO PROTECTION

The cost in manpower and materials of not protecting the coastline would be zero. However, there would be large losses of structures and land.

PRESENT PROTECTION

Three cities/towns in Senegal are presently protected by sea walls: Saint Louis, Rufisque, and Joal (located just north of the Saloum River mouth) (Figure 1). The major harbor in Senegal is in Dakar. The IPCC report (1990) estimates the cost of protecting harbors in Senegal at U.S. $43 million for a 1-meter rise in sea level. We used this estimate, scaled by sea level rise, for the cost of protecting the harbor, since we do not have the information to improve upon it. Under this option, the cost of protecting the harbor dominates the national cost of sea level rise (Table 7).

TABLE 7. PRESENT PROTECTION COSTS WITH AND WITHOUT HARBORS (MILLIONS OF 1990 U.S. DOLLARS)

Rise (m)	Without Harbors	With Harbors
0.5	$1-4	$23-26
1.0	3-6	46-49
2.0	10-13	96-99

IMPORTANT AREAS PROTECTION

We measured the length of the coastline (from the video record) characterized by medium to high development and at risk to sea level rise, and suggested protection options (Table 7). Only 68 km, or about 13 percent of the coastline, requires protection under this option. This includes a number of small fishing villages, whose residents often migrate seasonally, especially along the northern coast. The individual structures are rebuilt annually so they could be progressively relocated landward as sea level rose. Therefore, relocation at essentially no cost seems viable in these cases. In fact, it is likely that villages are already being relocated, due to present shoreline recession, albeit at slow rates. However, the social and cultural implications of this policy should be considered in more detail.

The costs of protection under this option are given in Table 8. The major cost is beach nourishment, with the 1-meter scenario comprising 75 to 85 percent of the total costs.

TOTAL PROTECTION

In Senegal, the population exceeds 10 people/km^2 along the entire coastline (Pelissier, 1983). Therefore, we estimated the cost of protecting the entire coastline of Senegal, including the dry land surrounding the Saloum/Diombos and Casamance Estuaries, and the Senegal Delta. All of the coastal lengths were measured using the video record, except the delta and estuaries which were measured on the maps. An additional 1,997 km of sea walls are required.

As shown in Table 8, the total costs of protection are about 2.5 to 4 times higher than the costs of protecting important areas.

TABLE 8. COSTS OF IMPORTANT AREAS AND TOTAL PROTECTION (MILLIONS OF 1990 U.S. DOLLARS AND PERCENT 1990 GNP)

Response	**Sea Level Rise (m)**		
	0.5	*1.0*	*2.0*
Important Areas			
Nourishment	$116-481	$190-714	$338-1,182
Sea Walls	8-73	22-88	68-132
Upgrading Harbors	21	43	86
Total	**146-575**	**255-845**	**492-1401**
% GNP	4-14	6-21	12-24
Total Protection			
Added Sea Wall Costs	261-847	718-1311	2,300-2,869
Total	**407-1,422**	**973-2,156**	**2,792-4,269**
% GNP	10-35	24-53	69-105

COMPARISON WITH IPCC PROTECTION COSTS

IPCC (1990) produced a worldwide estimate of the cost of a 1-meter rise in sea level using desktop methods. It did this on a country basis by estimating the cost of protecting all the low-lying coastline with a population of over 10 people/km^2. The low-lying coast includes all the estuaries and lower reaches of rivers that would be affected by sea level rise, along with harbors. Thus, the IPCC's estimate is based on maintaining the status quo, except in areas of very low population density.

IPCC estimated that protecting Senegal would cost U.S. $1,596 million. For our total protection case, which affords the same protection, we estimated costs of U.S. $973 to $2,156 million for the 1-meter scenario. Therefore, the IPCC estimate for Senegal falls between our low and high estimates.

However, the constituent costs in each case are different. For example, IPCC did not identify any requirement for beach nourishment in Senegal, while we found that this was a significant component of the costs. Also, IPCC estimated 1,353 km of coastline would require protection, while we estimated 2,065 km of coastline. These two factors alone raise our costs significantly compared to those in the IPCC Report. However, this increase in costs is compensated by our sea walls having a lower average cost. This demonstrates the need for continuing efforts to better predict protection and other costs associated with sea level rise at the national level.

APPROPRIATE RESPONSES TO SEA LEVEL RISE

The cost of protecting Senegal against sea level rise will present major costs for the nation's economy. Assuming Important Areas Protection and that this investment occurred over 50 years (2050 to 2100), it would represent an annual cost of 0.9 to 3.0 percent of the national gross investment (1987 value). If sea level rise occurs, the most appropriate response would be to protect the important areas. Only 3 percent of the total coastline would be protected, which would cost 25 to 40 percent less than protecting the entire coastline. (The disparity between length of area protected and cost is due to beach nourishment, as already described.) It is questionable what benefits Senegal would gain from the additional expenditure of total protection. Much of the land protected is of extremely low value, and such a policy would maximize wetland losses in these areas (c.f. Titus et al., 1991). Thus, the population criteria (10 people/km^2) used by IPCC (1990) for selecting what low-lying coastal areas should be protected appears to be inappropriate in the case of Senegal.

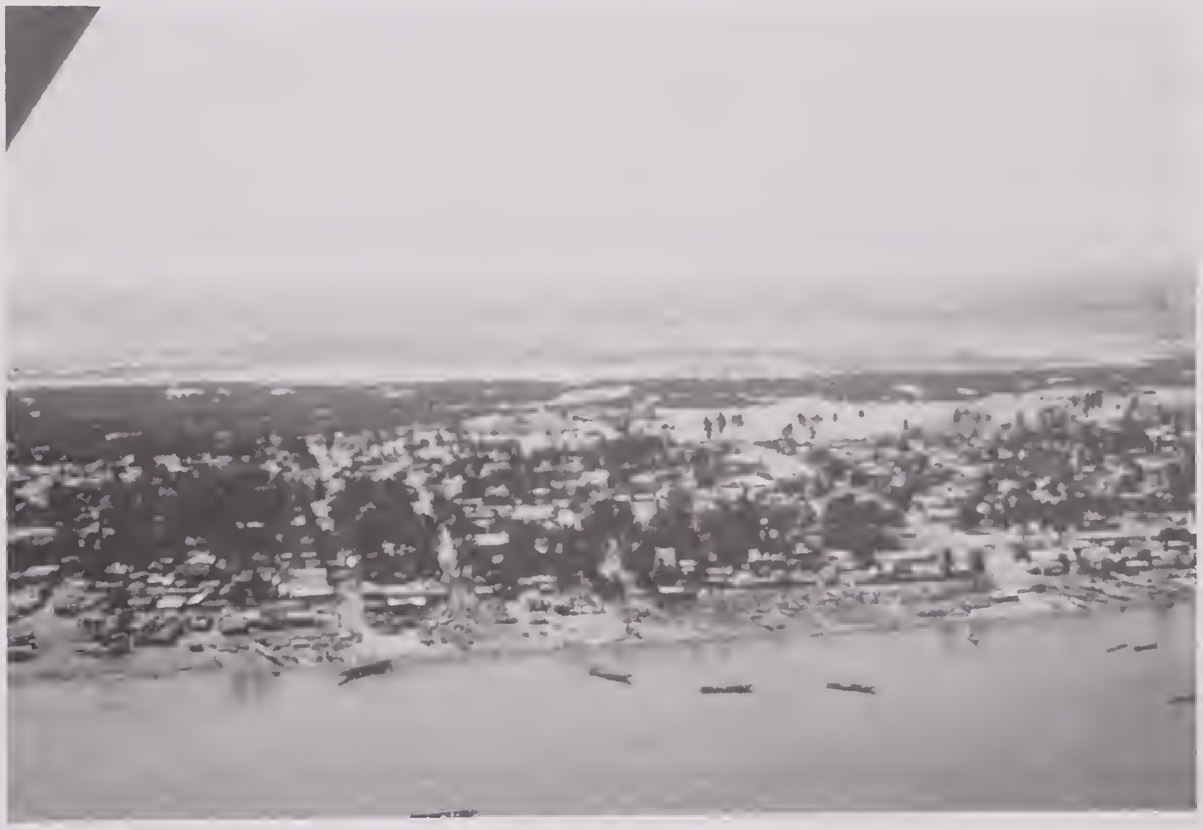
The major cost of Important Areas Protection is beach nourishment of tourist beaches. These beaches are very important to Senegal since tourism is a major and growing element of the economy. Beach nourishment would be essential to stop the destruction of tourist facilities given sea level rise. However, the nourishment costs have a large range due to the uncertainty in the quantity of pumped sand required to combat erosion. Since the cost of beach nourishment is both uncertain and high, flexible decisions regarding the application of beach nourishment are desirable. At present, a large portion of the tourist beaches in Senegal are developed with a single row of tourist houses and villas along the beach. Some form of retreat from the shoreline may be possible in the future, particularly if these structures have a short life. Alternatively, future development could follow a different model with more concentrated tourist development, or alternatively building setbacks.

In contrast, sea wall and harbor costs are comparatively small under Important Areas Protection. Since a large number of the residential and industrial regions of Senegal are located directly on the shoreline, protection of these coasts will be essential. The Dakar Harbor must also be protected as it is crucial to the economic health of Senegal.

The results presented here only represents the situation that would occur if sea level rose with present patterns and levels of development. Rapid development of the coastal zone of Senegal is to be expected in the coming century due to (1) high birth rates, (2) significant immigration from the Sahelian region due to drought, and (3) continued development of the tourist industry. To reduce the impact of any future sea level rise on these developments, the Senegalese government should develop a coastal zone management plan. This plan should include setback zones for the construction of new buildings, keeping additional coastline that would require protection to a minimum. For future tourist resorts, all major buildings would be placed back from the shore, with only easily moved structures adjacent to the beach (c.f. National Research Council, 1990). In particular, low-lying sandy barriers backed by wetlands (which occur at the mouth of the estuaries) should not be developed (Figure 8).

A complementary strategy that would minimize Senegal's future vulnerability to sea level rise would be to encourage population growth away from the coastline, reversing the existing trend.

FIGURE 8. THE CITY OF JOAL, LOCATED ON A SANDY BARRIER BACKED BY MANGROVE WETLANDS



FOLLOW-UP STUDIES

Follow-up studies to this work should include:

1. Historical analysis of shoreline evolution and longshore transport rates. This would provide data to calibrate predictions of future shoreline behavior and, hence, would yield better estimates of physical impacts.

2. Topographic analysis of the major urban coastal areas, particularly Greater Dakar. The importance of the coastal areas to Senegal has been demonstrated, and cheap and simple topographic surveys analyzed for enhanced flooding, inundation, and erosion would be useful.

3. A detailed analysis of the use of Dakar's drinking-water aquifer, with regard to the problems of population growth and climate change, particularly sea level rise.

ACKNOWLEDGMENTS

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THE IMPACTS OF SEA LEVEL RISE ON THE COASTLINE OF URUGUAY

Claudio R. Volonté
Lavandeira 364
Canelones, Uruguay

Robert J. Nicholls
Laboratory of Coastal Research
University of Maryland
College Park, Maryland

SUMMARY

About 65 percent of Uruguay's coast is comprised of sandy beaches. Every summer, the country's coastal resorts attract more than 1 million visitors and $200 million in revenue.

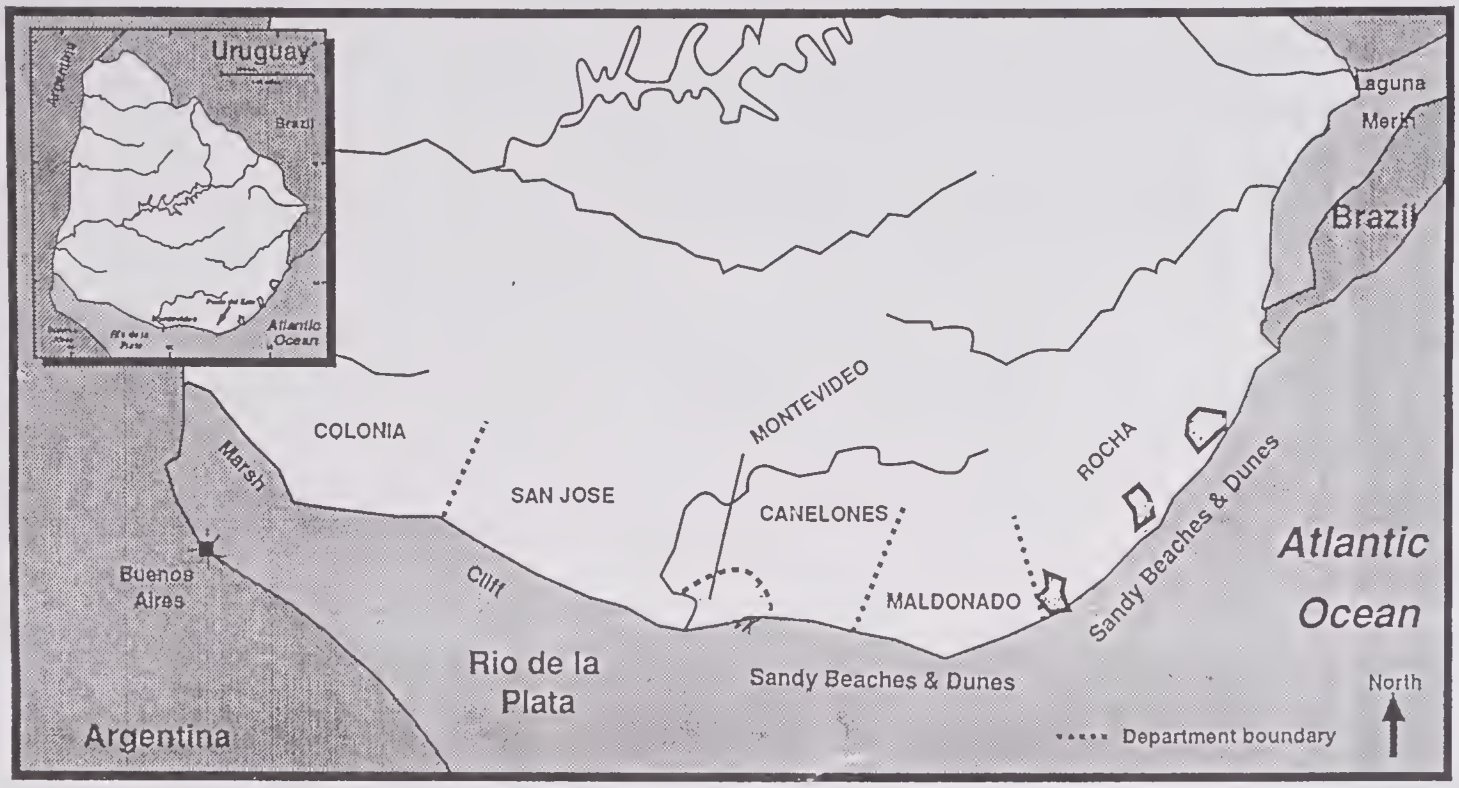
Uruguay has already reduced some of its vulnerability to erosion and sea level rise as the coastline has been made public land and new buildings have to be set back 250 meters from the shoreline. Existing coastal boulevards also provide a de facto setback for the first row of development. Nourishing 84 km of the shoreline is proposed as the most appropriate method of protecting the coastal developments behind the beaches against a 1-meter rise in sea level. However, this would be extremely costly—$2.9–$8.6 billion. If it is assumed that this investment would occur uniformly over 50 years (2050 to 2100), this represents annual expenditures of 6.5–19.2 percent of Uruguay's gross national investment in 1988 on coastal protection. It is also unclear if sufficient sources of sand are available.

BACKGROUND

Uruguay's coast is about 677.5 km long, with borders on the Río de la Plata (440 km) and the Atlantic Ocean (237.5 km) (Figure 1). Of the 19 geopolitical subdivisions (departments) of Uruguay, six are coastal. From west to east, Colonia, San José, Montevideo, Canelones and part of Maldonado have coasts on the Río de la Plata, and the rest of Maldonado and Rocha have coasts on the Atlantic Ocean. More than 2 million people live in these departments, according to the 1985 census, which is about two-thirds of the total population (Dirección General de Estadísticas y Censos, 1985).

The two main economic activities on the coast are tourism (both national and international) and ports (both for recreational and for fishing and shipping). Tourism is by far the more important activity, bringing to the country more than $235 million (1991 U.S. dollars) and 1 million overseas visitors annually, mainly during the summer (OPP/OAS/IDB, in press). Colonia, Montevideo, Atlántida, Piriápolis, the world famous Punta del Este (which attracts 43 percent of the incoming annual tourism), and La Paloma are Uruguay's most popular coastal resorts with a highly developed tourism infrastructure. In recent years, Cabo Polonio, Valizas, and Aguas Dulces have been growing increasingly popular. Montevideo is the major port but Colonia, and La Paloma are of increasing importance.

FIGURE 1. COASTLINE OF URUGUAY: ENVIRONMENTS AND POLITICAL DIVISION



COASTAL CHARACTERISTICS

In general terms, the coast of Uruguay consists of a sequence of sandy beaches separated by rocky headlands or other geographic landmarks. Table 1 shows a classification of the Uruguayan coast.

TABLE 1. CLASSIFICATION OF THE URUGUAYAN COAST (KM)

Department	Marshland	Sandy Beach	Cliffs (eroding)	Rocky/ Grassy Headland	Rocky Headland/ Coast	Port	Sea Wall	Total
Colonia	61.3	64.1	25.4	5.5	1.5	1.5	2.8	162.1
Percent	*37.8*	*39.5*	*15.7*	*3.4*	*0.9*	*0.9*	*1.8*	*23.9*
San José	7.9	39.0	38.9	0	0	0	0	85.8
Percent	*9.2*	*45.5*	*45.3*	*0*	*0*	*0*	*0*	*12.6*
Montevideo	3.7	18.0	0	22.8	14.8	7.0	6.3	72.6
Percent	*5.1*	*24.8*	*0*	*31.4*	*20.4*	*9.6*	*8.7*	*10.7*
Canelones	0	59.1	4.9	0	0.8	0	0	64.8
Percent	*0*	*91.2*	*7.6*	*0*	*1.2*	*0*	*0*	*9.5*
Maldonado	0	85.5	0	0	11.3	1.8	5.0	103.6
Percent	*0*	*82.5*	*0*	*0*	*10.9*	*1.7*	*4.9*	*15.3*
Rocha	0	174.3	0.9	1.7	10.1	1.6	0	188.6
Percent	*0*	*92.4*	*0.5*	*0.9*	*5.4*	*0.8*	*0*	*28.0*
Total	72.9	440.0	70.1	30.0	38.5	11.9	14.1	677.5
Percent	*10.8*	*64.9*	*10.3*	*4.4*	*5.7*	*1.7*	*2.2*	*100.0*

The western coast presents a narrow coastal zone of marshlands combined with sandy sediments due to the low wave action and large sediment load brought by the Uruguay and Parana rivers. Also in this area there are about 60 km of cliffs (Barrancas de San Gregorio and Barrancas de Mauricio), mainly of sandy-lime and clay materials. East of Montevideo are extensive sandy beaches and a sequence of coastal lagoons, almost completely isolated from the marine environment by coastal barriers and spits. About 26 km (or 3.9 percent) of the shoreline is modified by either ports (11.9 km) or sea walls (14.1 km).

Tidal ranges in Uruguay are relatively small, between 0.4 and 0.6 meters, but the southeasterly winds produce storm surges on average of 1.9 (Río de la Plata), 2.7 (Montevideo), and 3.7 meters (Colonia) (Jackson, 1985). Therefore, these high-value storm surges can increase the impacts of sea level rise during storms.

LOW-LYING LAND

As depicted in Table 1, Colonia contains Uruguay's most extensive marshes, with more limited development in San José and Montevideo. These areas coincide with the lower wave energy of the Río de la Plata. Most of the marshlands occur in narrow zones backed by relatively high-relief coastal plains or cliffs that would make it difficult for the marshes to migrate inland in response to sea level rise. Overall, wetlands represent about 10 percent of the Uruguayan coast.

Low headlands are also vulnerable to inundation by higher sea levels. Termed "rocky/grassy headlands" in Table 1, they currently suffer flooding and wave run-up during storm surges. Even though this type of coast comprises a small percentage of the Uruguayan coast, some important industrial zones (mainly in Montevideo, Figure 2) and urban areas (in Maldonado and Rocha) are located here. Sea level rise may cause limited permanent inundation and more frequent flooding.

FIGURE 2. ROCKY/GRASSY HEADLAND WITH INDUSTRY, IN THE DEPARTMENT OF MONTEVIDEO

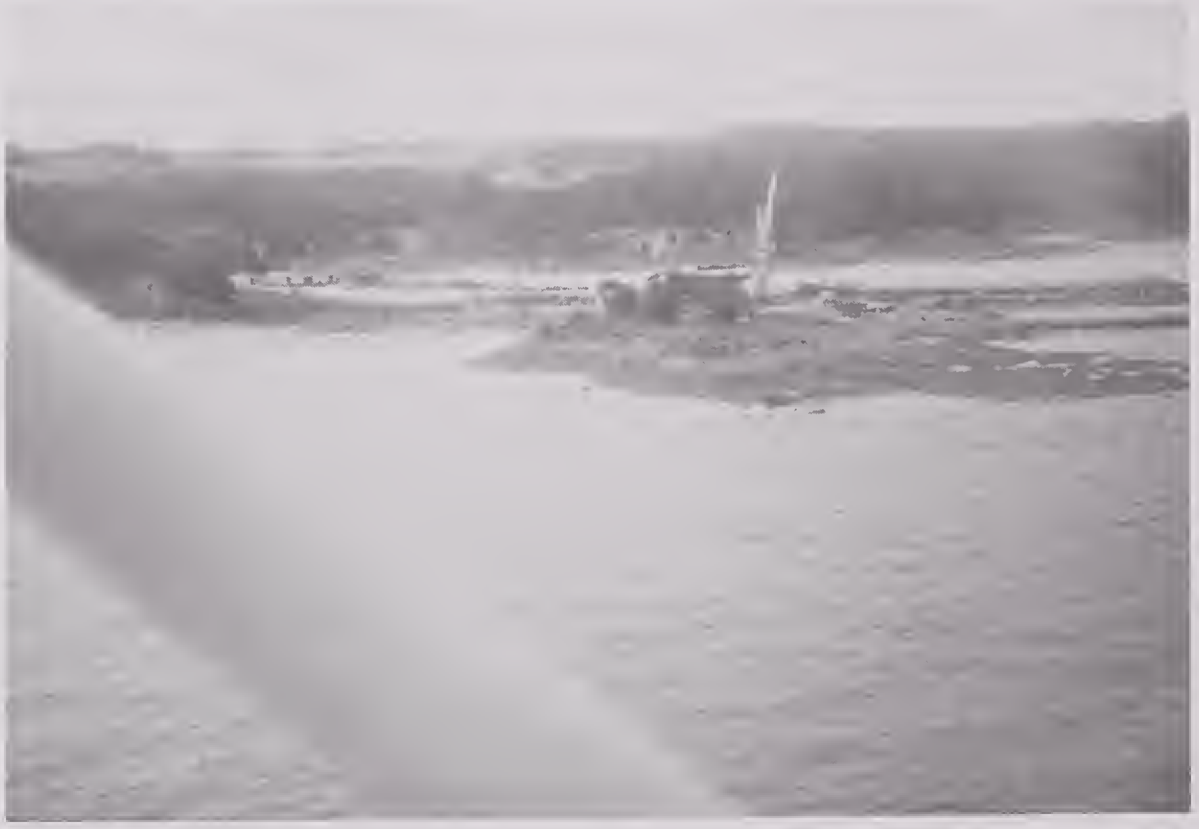


Photo by Gustavo Barrios, June 1991.

CLIFFS

Cliffs in Uruguay predominate on the western coast, mainly in Colonia and San José. The most typical cliffs are the Barrancas de Mauricio and San Gregorio. They are erodible sedimentary cliffs formed mainly of sandy-lime and clays. They extend along 60 km of coastline and can reach heights of up to 20 meters. They are presently eroded by wave action coming from the southwest. Estimates have shown erosion rates of up to 20 meters in 25 years (Jackson, unpublished), or about 0.8 meters per year. Therefore, they are highly vulnerable to sea level rise, which will increase wave energy and allow wave attack at higher levels on the face of the cliffs.

SANDY BEACHES

Sandy beaches occur along the entire coast of Uruguay, comprising about 65 percent of the coast. Beach width varies from 30 to 250 meters, but is typically between 50 and 100 meters, with the narrowest beaches occurring in the western part of the country. In general, sandy beaches in Uruguay have a well-defined dune system, with dune heights of up to 10 meters in some cases. Along most of the Uruguayan coast, both the natural beach width and the dune system have been maintained, even in urban areas.

EXISTING PROTECTION AND PORT INFRASTRUCTURE

Several areas of the coast of Uruguay are presently protected by some type of structure (Table 2). In addition, several ports have built structures to protect their harbors. The most important ports from west to east are Colonia, Montevideo, Piriápolis, and La Paloma.

TABLE 2. EXISTING SEA WALLS

Site	Length (km)	Height (m) (above mean sea level)
Colonia (city)	2.25	6
Montevideo		
El Cerro	2.25	No information
Downtown	10	4
La Floresta	2	No information
Piriápolis	2.25	2.6
Punta del Este	5	4

ANALYTICAL METHODS

The present study quantifies the following:

1. The land at risk from erosion and inundation caused by sea level rise.
2. The economic value of the land and infrastructure at risk.
3. The cost of protecting coastal land and infrastructure for various protection scenarios.

Two main effects are considered: inundation of low-lying areas, and increasing erosion. Other consequences of sea level rise, such as saltwater intrusion to water tables and aquifers, are not considered here.

SEA LEVEL RISE SCENARIOS

This study assumes four arbitrary scenarios of eustatic sea level rise for the year 2100: 0.2 (no acceleration, which is the present trend), 0.5, 1.0, and 2.0 meters. The absence of serious subsidence, tectonic activities, and sufficiently long records on the position of mean sea level (Emery and Aubrey, 1991) on the coast of Uruguay validates this assumption.

AERIAL VIDEOTAPE-ASSISTED VULNERABILITY ANALYSIS

For this study, Volonté videotaped the Uruguayan coast from a small plane at 50 meters elevation, except where local regulations prohibited this altitude. From the video record, the authors have extracted information on relative topography, geomorphology, land use, and human activities. They also employed the Aerial Videotape-Assisted Vulnerability Analysis (Dennis et al., 1991; Niang et al., in these proceedings; Nicholls et al., 1992a).

FIELDWORK

Ground surveys give occasional high-quality data points of elevations that, with the aid of the video record, can be interpolated along the shore. Seven profiles were measured at selected sites near Colonia, Juan Lacaze, Atlántida, Piriápolis, José Ignacio, Punta del Este, and Barra del Chuy (Figure 1). In addition, Volonté interviewed coastal experts within the Department of Hydrology in the Ministry of Housing, Land Use, and Environment.

ESTIMATES OF LAND AT RISK

The land-at-risk model was applied to the entire coast of Uruguay, by a process of either erosion or inundation. Each of the sea level rise scenarios produced a new position of the shoreline and, therefore, an area of land at risk. A typical analysis examined the type of land form (marshland, sandy beach, cliff, soft or rocky headland), and associated physical parameters (active length, height, and width of profile). The dominant land-loss process under sea level rise was determined, and the appropriate land-at-risk model was applied.

EROSION

The Bruun Rule is much used to calculate erosion due to sea level rise. (For a full description of the erosion model and the Bruun Rule, refer to Niang et al., in these proceedings). The depth of closure is the variable in the Bruun Rule equation that is the most difficult to estimate. For our calculations we used two depths, d_{L1} and d_{L100}, representing the greatest depths where intense on/offshore and alongshore transport will occur within a typical year or within 100 years, respectively. We obtained d_{L1} by using Hallermeier's (1981) model and assumed that d_{L100} was 1.75 times larger than d_{L1} (Nicholls et al., 1992b). Using wave data from a Uruguayan national assessment report, (Ministerio de Transporte y Obras Públicas/UNDP, 1979) we determined d_{L1} and then d_{L100} (see Table 3). We decided to use only one value of depth of closure (d_{L1}) for the Río de la Plata coast because of its shallow conditions. The two values give a range of estimates of land loss due to erosion, according to the erosion model used in this study.

Recession of cliffs were estimated by using a dynamic equilibrium concept, similar to the Bruun Rule.

TABLE 3. DEPTH OF CLOSURE (M) FOR THE COAST OF URUGUAY

Location	Low (d_{L1})	High (d_{L100})
Carmelo (Colonia) to Punta Gorda (Montevideo)	3	NA
Punta Gorda (Montevideo) to Fortín de Santa Rosa (Canelones)	5	NA
Fortín de Santa Rosa (Canelones) to Atlántida (Canelones)	9	9
Atlántida (Canelones) to Piriápolis (Maldonado)	10	10
Piriápolis (Maldonado) to Chuy (Rocha)	10	17.5

NA: Not applicable.

INUNDATION

In the case of marshlands and other coastal lowland, we applied a straightforward inundation or "drowning" concept. A known contour is marked on a map or estimated from the video record, and then the distance to the water line is determined. A constant gradient of slope is assumed, and the level of the sea (or location of water line) is raised. The new water line is calculated, and the land seaward of this land is inundated and assumed lost. We have not estimated a rate of retreat of marshes inland.

OPTIONAL RESPONSES TO SEA LEVEL RISE AND ECONOMIC VALUE OF LAND AT RISK

The responses to sea level rise presented in this study range from doing nothing and letting the shoreline move landward and erode the coast to protecting the entire country's coastline. This section presents four types of responses: (1) retreat or abandonment of the coast, assuming that no protection will be planned; (2) upgrade of existing protection as sea level rises; (3) protection of only important areas of the country, mainly, cities, tourist beaches, ports, and industries; and (4) protection of the entire coast with a population density greater than or equal to 10 people/km^2.

RETREAT OR ABANDONMENT

We used the video record and ground surveys to obtain information on the types and number of structures in urban centers and types of land uses along the coast. In addition, the 1985 national housing census (Dirección Nacional de Estadísticas y Censos, 1985) provides the number of structures per town. This gave us quantitative information on the density of development in each urban center. We built a data base of prices of land and buildings, based on interviews with local real estate agents and classified sections of local newspapers.

Wetlands were not valued due to the lack of suitable information. This does not reflect their high ecological value as a source of food and habitat for numerous animal and plant species or value as flood protection for the dry land behind (Constanza et al., 1989). In addition, we did not estimate the value of industries located on the coast, or the economic value of ports that would have to be closed if their protective structures were not upgraded.

To determine the number of structures that would be vulnerable under the retreat or abandonment option, we selected an urban center and then overlaid all projected shorelines. Structures seaward of these new lines were assumed to be destroyed, and their values were recorded. Both the land and structural values of urban real estate were assessed. In most cases, we assumed (realistically) that the width of the existing beach would be maintained and moved landward. Therefore, the width of the beach should be added to the horizontal retreat to determine the extent of the impact. In the case of rural land, we estimated an average value per hectare according to available sources, and then multiplied this value by the area assumed lost by the retreat model.

UPGRADE OF EXISTING PROTECTION

Almost 24 km of Uruguay's coast are currently protected by sea walls. This is longer than the length given in Table 1 because Playa Pocitos, La Floresta, and Piriápolis were included in the sandy beach category in the national classification. All other sea walls have no beach. In this case of protection we assumed that all sea walls mentioned will be upgraded to higher sea levels.

To calculate the cost of upgrading the sea walls, we designed four simple sea wall types. We then used costs per cubic meter in Uruguay of purchasing, transporting, and placing rock ($\$115/m^3$), along with design (10 percent) and maintenance costs (20 percent of total cost), to calculate the cost per kilometer of each sea wall. The four types of sea walls are basically a low and a high estimate for open or wave-exposed coasts, a sea wall for protecting cliffs (used in the next section), and a sea wall for sheltered areas. (For a full description of the sea wall designs, see Niang et al. in this proceedings.)

To upgrade existing protection for the 0.2-meter scenario, a sheltered sea wall was deemed appropriate. We proposed new sea walls of the low and high estimates types for the rest of the sea level rise scenarios. We assumed that the existing sea walls could withstand the 0.2-meter scenario, but not the higher scenarios. Because wave height is one of the main parameters in the design of the high-estimate sea wall, we decided to calculate the design of two sea walls, one for the Río de la Plata wave regime, and another for the Atlantic Ocean. We used a maximum significant wave height (H_{smax}) of 0.9 meters for the Río de la Plata, and 3.27 meters for the Atlantic Ocean, according to our previous wave regime calculations. Table 4 shows the volumes and prices of the different types of sea walls.

PROTECTION OF IMPORTANT AREAS

This response to sea level rise is based upon protecting medium to highly developed residential and tourist areas, plus other strategic areas, such as ports. It is considered to be the most likely protection option in the event of sea level rise. The areas to be protected under this case are: (1) towns or urban areas with structures that could be damaged by sea level rise; and (2) areas that already have protection (upgrade of existing protection).

TABLE 4. VOLUME (M^3) AND PRICE OF SEA WALL PER KM (THOUSANDS OF U.S. DOLLARS)

	Sea Level Rise Scenarios			
Type of Sea Wall	*0.2 m* *Volume/Cost*	*0.5 m* *Volume/Cost*	*1.0 m* *Volume/Cost*	*2.0 m* *Volume/Cost*
Sheltered	480/$72	1,500/$227	4,000/$607	12,000/$1,821
Low Estimate	496/$75	1,600/$242	4,400/$667	13,600/$2,064
High Estimate				
Río de la Plata	6,271/$951	7,891/$1,197	11,391/$1,729	21,391/$3,247
Atlantic Ocean	20,500/$3,111	22,120/$3,357	25,620/$3,889	35,620/$5,407

Based both on the video record of the coast and on the 1985 census of population and housing (Dirección General de Estadísticas y Censos, 1985), we examined the impact of sea level rise on every urban center. The setback, distance of structures from the water line, and the use of the urban center determined what response was appropriate. If no structure would be affected by the sea level rise scenarios, then no action is proposed for that scenario. However, if a structure would be affected, an appropriate action was proposed.

For instance, in some urban centers in Canelones, most of the structures are 200 to 300 meters from the present water line. With sea level rise, the beach will erode and move the entire profile landward, including the dry width of the beach and dune. This regression maintains the beach, which is the main asset of a tourist town. This action to preserve the beach is necessary, until the dune line intersects the first line of structures. Usually this is the case for sea level rise scenarios of 1 meter or higher.

The amount of sand for a nourishment project was calculated by estimating the volume of a layer of sand with the thickness of the assumed sea level rise scenario. The width of this layer goes from the first dune (including the dune) to the depth of closure. We assumed the cost of a cubic meter of sand to be $5. Large groins were added to both ends of the nourishment project, where necessary, to preserve longshore losses. (For a full description of the nourishment project's design refer to Niang et al. in these proceedings.)

Sea walls were also proposed in very few cases (mainly, low headlands and urban areas with no recreational beaches). The type of sea walls are described in the previous section. In addition, we designed another type of sea wall for protecting urban centers on eroding cliffs. Once again we have a low- and high-estimate type of sea wall for cliffs. Both types are the same as those used for the sandy coast (Niang et al., in these proceedings), except that the high-estimate type includes a 20-meter-wide arm from the top of the sea wall to the cliff face. The space between the sea wall, the cliff face, and the ground is filled with material at a cost of $\$5/m^3$. The costs of retrofiling the cliff or stabilization with other procedures, such as geotextiles, are not considered. The volume and cost of this type of sea wall are shown in Table 5.

PROTECTION OF THE ENTIRE COAST

The total protection case assumes that all coastal areas with more than 10 $people/km^2$ will be protected. This allows comparison with the IPCC (1990) estimates for the cost of a 1-meter scenario. In the case of Uruguay, all departments but Rocha have population densities greater than 10 people/km^2, according to the 1985 census. To estimate the cost of protection for the entire coast we need to add approximately 300 km of coastline. The rest of the coast, 176 km (26 percent of the total coast), either would have no impacts as it is hard-rock cliffs or corresponds to the department of Rocha.

The 300 km of coastline added to this case corresponds to coastal lands that presently are not used intensively by humans. About 60 km are cliffs, 62.2 km marshlands, 19.7 km of low headlands, and 160 km of sandy beaches. To protect these different coastlines, we used appropriate sea walls, as described in previous sections. Once again we have two estimates, depending on if we are using low or high estimates of the sea wall. In addition, we provide two estimates using the two depths of closure where appropriate.

TABLE 5. VOLUME (M^3) AND PRICE OF SEA WALL PER KM IN CASE OF COASTS WITH CLIFFS (THOUSANDS OF U.S. DOLLARS)

Type of Sea Wall	**Sea Level Rise Scenarios** *0.2 m* *Volume/Cost*	 *0.5 m* *Volume/Cost*	 *1.0 m* *Volume/Cost*	 *2.0 m* *Volume/Cost*
Low Estimate	496/$72	1,600/$242	4,400/$668	13,600/$2,064
High Estimate				
Río de la Plata	71,492/$1,800	87,567/$2,880	115,958/$4,748	178,740/$8,730
Atlantic Ocean	308,298/$5,073	333,056/$6,196	357,676/$8,135	466,916/$12,260

RESULTS

When comparing inundation and erosion impacts, erosion appears to be the most important impact of sea level rise in Uruguay due to the small extent of low-lying coastal areas. Coastal wetlands are the geomorphic coastal feature of the coast of Uruguay vulnerable to inundation.

Tourism is a growing generator of foreign income. From an economic point of view, tourism would be the most vulnerable sector of the economy. Erosion of sandy beaches could diminish the main focus of attraction for national and international summer tourism. Most tourists travel to Uruguay during the summer, about 60 percent (OPP/OAS/IDB, in press), and visit the resort areas along the coast. The most important and recognized tourist resorts are located east of Montevideo, in the departments of Canelones and Maldonado.

ESTIMATES OF LAND AT RISK

BY COASTAL TYPE

Sandy Beaches

Qualitatively, much of the Uruguayan coast would appear to have a low vulnerability to sea level rise because of the large quantity of sand, particularly in the form of dunes. However, the erosion model applied in this study (the Bruun Rule) estimated large shoreline recession for some areas. This was evident in parts of the department of Canelones, where the shoreline recession estimates reach up to 700 meters for sea level rise equal to or greater than 1 meter, even though there is a well-developed and high dune system behind the beach.

Practical experience and equilibrium models, such as the Bruun Rule, demonstrate that the concept of an active width of a beach is similar to an iceberg: what we see (dry sand) is only a small portion of the profile, most of it is under water (Leatherman, 1991). In Uruguay the coastal areas in the department of Canelones appear to have a wide active profile (reaching up to 6 km offshore). Thus, the results predict high shoreline recession. This is also the case for some areas of the department of Rocha, where the wave energy is high, and the active width over long time scales (100 years) may be as far as 13 km offshore. The new predicted position of the shoreline under sea level rise can show great damage to the coastal urban centers, not only because their structures can be affected, but because the beaches could deteriorate or even disappear.

Marshes

The marshes of the west coast of the country are very vulnerable to sea level rise. They could be affected even for low scenarios of sea level rise. It was estimated that most of marshlands would be destroyed for the 1- and 2-meter sea level rise scenarios, as no space is available for them to migrate upland. This is the case for such urban areas as Delta del Tigre in San José and Santiago Vázquez in Montevideo, which are fronted by marshlands. A fundamental problem for marshes in Uruguay is that most of them occur in narrow zones backed by high-relief coastal plains or cliffs that would make it difficult for them to migrate inland due to sea level rise.

Sandy Barriers

Another environment that could be very vulnerable to the accelerated rise of sea level is the sandy barriers of the eastern coast. These barriers separate the ocean from interior lagoons, such as Laguna Garzón and Rocha. They are located in areas of high wave energy, and during storms they are already overwashed and even breached. This type of landform is very vulnerable to sea level rise, and even low scenarios suggest their destruction, causing environmental damage to the interior coasts of the lagoon. Fortunately, most of these narrow barriers are undeveloped.

BY DEPARTMENT

Table 6 summarizes the total land at risk for the different sea level rise scenarios and depths of closure. It shows that the greatest impact on the coastal zone could occur for scenarios of sea level rise of 1 meter or more. As stated before, the concept of d_{L100} is only applicable for the departments of Maldonado and Rocha and sandy coastlines. If we define the coastal zone as a 5-km strip of land, landward of the sea, the total coastal zone area is approximately 3,400 km^2. The worst case scenario of 2 meters can produce a loss ranging from 5 to 8.4 percent of the coastal zone defined in this way. This land is the most valuable land of the coastal zone and possibly of the entire country. The magnitude of land at risk varies from place to place. Following are the estimates of this land by department.

Colonia

In the department of Colonia, the major impact of low scenarios of sea level rise is inundation of wetland areas. For scenarios greater than or equal to 1 meter, some of the sandy beaches show impressive erosion, averaging 100 to 300 meters. In the areas around Arroyo Cufré, Santa Regina, and Brisas del Plata, recession is up to 500 meters. The two major cities of this department, Colonia and Juan Lacaze, experience shoreline recession of up to 250 meters on their sandy coasts, which would destroy the first block of urban development.

TABLE 6. TOTAL LAND AT RISK (KM^2) UNDER SEA LEVEL RISE SCENARIOS

DEPARTMENT	EROSION		INUNDATION		TOTAL
	Sandy Beach	Cliffs	Marshland	Rocky/Grassy Headland	
			0.2-m Scenario		
Colonia	2.1	0.3	0.8	0.1	3.3
San José	1.2	0.5	0.3	0	2.0
Montevideo	0.3	0	1.2	0.1	1.6
Canelones	2.8	0.3	0	0	3.1
Maldonado	1.5/4.4	0	0	0	1.5/4.4
Rocha	3.7/9.5	0	0	0	3.7/9.5
Total	**11.6/20.3**	**1.1**	**2.3**	**0.2**	**15.2/23.9**
			0.5-m Scenario		
Colonia	5.2	0.8	2.1	0.1	8.2
San José	3.1	1.3	0.8	0	5.2
Montevideo	0.6	0	3.0	0.2	3.8
Canelones	7.1	0.6	0	0	7.7
Maldonado	3.8/11.0	0	0	0	3.8/11.0
Rocha	12.9/33.7	0	0	0	12.9/33.7
Total	**32.7/60.7**	**2.7**	**5.9**	**0.3**	**41.6/69.6**
			1.0-m Scenario		
Colonia	10.4	1.5	4.2	0.1	16.2
San José	6.1	2.6	1.6	0	10.3
Montevideo	1.2	0	6.0	0.4	7.6
Canelones	14.2	1.3	0	0	15.5
Maldonado	.6/22.0	0	0	0	7.6/22.0
Rocha	25.7/67.4	0	0	0	25.7/67.4
Total	**65.2/121.3**	**5.4**	**11.8**	**0.5**	**82.9/139.0**
			2.0-m Scenario		
Colonia	22.0	3.1	8.0	0.2	33.3
San José	12.3	5.2	3.2	0	20.7
Montevideo	2.5	0	12.0	0.7	15.2
Canelones	28.2	2.6	0	0	30.8
Maldonado	15.1/54.4	0	0	0	15.1/54.4
Rocha	51.5/131.4	0	0	0	51.5/131.4
Total	**131.6/250.8**	**10.9**	**23.2**	**0.9**	**166.6/285.8**

San José

The department of San José shows a similar pattern. Marshland will be affected even for the low scenarios. For scenarios of 1 meter and higher, most of the marshland could be destroyed, and such towns as Delta del Tigre, which are behind marshlands, could be affected. The eroding cliffs will suffer retreats of up to 150 meters. The most vulnerable areas besides marshlands are the many low-lying river mouth areas, which could inundate low inland areas.

Montevideo

Montevideo's mostly undeveloped western portion has a combination of pocket beaches and low rocky/grassy headlands. This area will suffer minor impacts, the most important being inundation of wetlands around Santiago Vázquez. The coast of the bay, including the densely developed peninsula of Santa Teresa ("Old Town") is mainly protected by a sea wall or other protective structures for the port. East of the Bay, from Playa Pocitos to Punta Gorda is a sequence of pocket beaches and rocky headlands. This area, which has intensive recreational and residential use, will experience shoreline recession of up to 200 meters, for scenarios of 1 meter and greater, if no protective measures are taken. East of Punta Gorda to the border with the department of Canelones lie 6 km of straight sandy beaches. This area coincides with the city's most expensive real estate. Erosion can move the shoreline up to 150 meters inland for the 1-meter scenario. Most of the development in this area is behind the first dune and a coastal boulevard, so damage to buildings should be minimal.

Canelones

The entire coast of the department of Canelones consists of a series of towns protected by sandy beaches subjected to continuous urban land use. Extensive shoreline recession of 700 meters for the 2-meter sea level rise scenario was estimated mainly in areas east of Atlántida. Even though this area has a well-developed dune system of up to 8 meters high, the depth of closure can be as far as 6 km offshore. This recession may cause the complete destruction of some coastal towns. More detailed studies should be done in these areas.

Maldonado

The department of Maldonado has shorter sandy beaches because of the presence of more frequent rocky headlands. The impacts on these coastal land forms are somewhat less than those of Canelones. The average recession for 2-meter scenario reaches 200 meters. Most of these areas have well-developed sand dunes and relatively deep waters offshore. In the city of Piriápolis, present erosion problems could increase with higher sea levels: waves could reach the city's sea wall even during low tides. In the city of Punta del Este, the most vulnerable coast seems to be the beaches west of the peninsula. This may be an overestimation, because easterly winds protect this area from major wave action. East of Punta del Este, the wave action increases, along with the depth of the offshore waters. The most vulnerable area will be the narrow sandy barriers of the Laguna Garzón on the border with Rocha that could be breached.

Rocha

When the erosion model is applied to the coast of the department of Rocha, recession figures can reach up to 300 meters for sea level rise scenarios of 1 meter or more, mainly east of La Paloma, Valizas, Aguas Dulces, and La Coronilla. We also calculated an extreme case by using an active width to depths of d_{L100}, that sometimes can have a length of 13 km. The vulnerability of the coast when the erosion model is applied with these parameters is enormous. Under the 1-meter scenario, recession can reach up to 1 km from present shoreline position, with the possibility of the destruction of entire urban centers if no protection is provided. Fortunately, this part of the coast of Uruguay is scarcely populated. Another important finding is the vulnerability of the narrow barrier that separates the coastal lagoons from the sea. Some are periodically breached, but an increase in sea level would make overtopping a more frequent event or would even create permanent opening, disrupting the low-lying environments of the lagoon's shores.

ECONOMIC VALUE OF LAND AT RISK

RETREAT OR ABANDONMENT

Table 7 presents a summary per department of the economic value of structures and land affected by the different scenarios of sea level rise. At a national scale, we estimated this economic value to range from $13 million to almost $3 billion, depending on the sea level scenario. These values are minimum values; adding the values of marshlands, industries, and harbors would better indicate the actual value of coastal infrastructure and land at risk from sea level rise. To obtain a more realistic estimate of the economic impact, we would need to introduce the ramifications of these impacts on the national economy, such as loss of tourism income and employment and loss of industrial and port employment. Therefore, a straight benefit-cost analysis with the figures shown in Table 7 is misleading (numbers are not discounted in time).

At the department level, Colonia seems to experience large structural losses, even for small changes in sea level. The cities of Juan Lacaze and Colonia account for most of the structures. The departments of Montevideo and Maldonado will suffer the greatest economic losses, mainly for sea level rise scenarios of higher than 1 meter. In Maldonado, losses occur in the city of Piriápolis and along Punta del Este, the site of very valuable coastal real estate. The minimal impacts in the department of Canelones are mainly due to the fact that most of its coast is developed behind a 200- to 250-meter buffer zone. Thus, a significant number of structures are only lost for sea level rise scenarios of higher than 1 meter.

UPGRADE OF EXISTING PROTECTION

Existing ports also require protection, the most important being from west to east: Colonia, Montevideo, Piriápolis, and La Paloma. IPCC Working Group III (1990) estimates the cost of protecting these ports at $4.4 million for a 1-meter rise in sea level. We used this estimate since we do not have, at this time, the information that could improve it. For the 0.2-meter rise (present trend) scenario, we used a cost of $0.88 million; for 0.5 meters, $2.2 million; and for 2.0 meters, $8.8 million. Table 8 summarizes the total cost required to protect the coast that is today protected. The low and high estimates refer to the low and high types of sea wall.

PROTECTION OF IMPORTANT AREAS

Table 9 presents the estimated costs for protecting the important areas along the coast of Uruguay. In each case, nourishment accounts for more than 95 percent of the total cost of protection. The major portion of the nourishment cost is the construction of the large groins. Also, the higher the sea level rise scenario, the greater the length of coastline needing protection. These estimates show the serious impacts that sea level rise could cause in the Uruguayan economy if sandy beaches and coastal real estate are to be preserved. Even present conditions (a 0.2-meter rise) necessitate large expenditures on beach nourishment.

TABLE 7. ECONOMIC VALUE OF STRUCTURES AND RURAL LAND VULNERABLE TO SEA LEVEL RISE (MILLIONS OF U.S. DOLLARS)

Department	Structure	Rural Land	Total
	d_{L1}/d_{L100}	d_{L1}/d_{L100}	d_{L1}/d_{L100}
0.2-m Scenario			
Colonia	4.2	0.2	4.4
San José	0	0.1	0.1
Montevideo	0	0.03	0.03
Canelones	7.5	0.2	7.7
Maldonado	2.2/2.2	0.09/0.26	2.3/2.5
Rocha	6.4/10.2	0.15/0.38	6.6/10.6
Total	**20.3/24.1**	**0.77/1.17**	**21.1/25.3**
0.5-m Scenario			
Colonia	14.9	0.5	15.4
San José	0.5	0.2	0.7
Montevideo	0	0.1	0.1
Canelones	43.2	0.5	43.7
Maldonado	106.5/1,194.0	0.2/0.6	106.7/1,194.6
Rocha	16.0/32.3	0.5/1.4	16.5/33.7
Total	**181.1/1,284.9**	**2.0/3.3**	**183.1/1,288.2**
1.0-m Scenario			
Colonia	33.6	1.0	34.6
San José	1.9	0.4	2.3
Montevideo	340.0	0.2	340.2
Canelones	106.8	1.1	4.6
Maldonado	1,300.3/1,368.7	0.5/1.3	1,300.8/1,370.0
Rocha	31.5/62.4	1.0/2.7	32.5/65.1
Total	**1,814.1/1,913.4**	**4.2/6.7**	**1,818.3/1,920.1**
2.0-m Scenario			
Colonia	71.2	2.0	73.2
San José	5.7	0.7	6.4
Montevideo	1,042.9	0.3	1,043.2
Canelones	240.0	2.2	10.1
Maldonado	1,621.9/1,644.8	0.9/2.2	1,622.8/1,647.0
Rocha	61.7/88.9	2.1/5.3	63.8/94.2
Total	**3,043.4/3,093.5**	**8.2/12.7**	**3,051.6/3,106.2**

TABLE 8. COST OF UPGRADING EXISTING PROTECTION (MILLIONS OF U.S. DOLLARS)

	Sea Level Rise Scenarios			
	0.2	*0.5*	*1.0*	*2.0*
	Length - Cost (km) Low/High	Length - Cost (km) Low/High	Length - Cost (km) Low/High	Length - Cost (km) Low/High
Harbors[1]	11.9 - $0.9	11.9 - $2.2	11.9 - $4.4	11.9 - $8.8
Sea Wall[2]	23.8 - $1.7	23.8 - $5.8/44.1	23.8 - $15.8/56.7	23.8 - $49.1/92.8
Total	**35.7 - $2.6**	**35.7 - $8.0/46.3**	**35.7 - $20.2/61.1**	**35.7 - $57.9/101.6**

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[1] Based on IPCC (1990).

[2] For the 0.2-meter scenario, sheltered sea walls are assumed; present design will support added volume. For the other scenarios, low and high types of sea walls are assumed (refer to text).

TABLE 9. COST OF PROTECTING IMPORTANT AREAS (MILLIONS OF U.S. DOLLARS)

Sea Level Rise Scenario		**Response**		**Total**
	Upgrade Existing Protection[1]	*Sea Walls*	*Nourishment*[2]	
0.2 Meter				
Km	35.7	21.6	47.1	104.4
Cost (d_{L1}–d_{L100})[3]	$2.6-NA	$1.7-18.8	$1,340.2-5,444.2	$1,344.5-5,465.6
0.5 Meter				
Km	35.7	27.7	70.1	133.5
Cost (d_{L1}–d_{L100})	$8.0-46.3	$6.9-40.7	$2,053.5-6,784.1	$2,068.4-6,871.1
1.0 Meter				
Km	35.7	30.7	84.3	150.7
Cost (d_{L1}–d_{L100})	$20.2-61.1	$21.4-70.2	$2,861.2-8,446.4	$2,902.8-8,577.7
2.0 Meters				
Km	35.7	39.6	105.5	180.8
Cost (d_{L1}–d_{L100})	$57.9-101.6	$53.9-203.5	$4,645.8-11,496.9	$4,757.6-11,802.0

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[1] See Table 6 for breakdown of costs.

[2] Added sand plus cost of groins.

[3] Low estimate (d_{L1}) and high estimate (d_{L100}).

PROTECTION OF THE ENTIRE COAST

Table 10 depicts the calculations for protecting the entire coast. It is clear from these figures that nourishment projects are still the major cost of protecting the Uruguayan coast, accounting for more than 90 percent of the total cost.

TABLE 10. COST OF PROTECTING THE ENTIRE COAST
(MILLIONS OF U.S. DOLLARS) [1]

Sea Level Rise Scenarios		Response		Total
	Upgrade Existing Protection[2]	*Protection of Important Areas*[3]	*Sea Walls*	
0.2 Meter				
Km	35.7	104.4	354.5	494.6
Cost (d_{L1}–d_{L100})[4]	\$2.6-NA	\$1,344.4-5,465.6	\$26.4-509.6	\$1,373.5-5,977.8
0.5 Meter				
Km	35.7	133.5	357.9	527.1
Cost (d_{L1}–d_{L100})	\$8.0-46.3	\$6.9-40.7	\$85.3-587.5	\$2,161.7-7,504.9
1.0 Meter				
Km	35.7	150.7	340.7	527.1
Cost (d_{L1}–d_{L100})	\$20.2-61.1	\$2,902.8-8,577.9	\$220.9-797.8	\$3,143.9-9,436.6
2.0 Meters				
Km	35.7	180.8	310.6	527.1
Cost (d_{L1}–d_{L100})	\$57.9-101.6	\$4,757.6-11,802.0	\$616.6-1,284.6	\$5,432.1-13,188.2

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[1] Does not include the coast of the Department of Rocha because this department has fewer than 10 people/km^2.

[2] See Table 6 for breakdown of costs.

[3] See Table 8 for breakdown of costs.

[4] Low estimate (d_{L1}) and high estimate (d_{L100}).

COMPARISON WITH IPCC RESULTS

The IPCC (1990) produced a worldwide estimate of the cost of a 1-meter rise in sea level using desktop methods. It did this on a country basis by estimating the cost of protecting all the low-lying coastline with a population of over 10 people/km^2. The low-lying coast includes all the estuaries and lower reaches of rivers that would be affected by sea level rise. Thus, the IPCC estimate is based on maintaining the status quo, except in areas of very low population density.

The IPCC report estimates the cost of protecting Uruguay at \$1,805 million for a 1-meter rise in sea level. This includes upgrading harbors, protecting low coasts and coastal cities, and nourishing sandy beaches. The IPCC's calculations assume total protection, as described above. Even though the two studies have a similar approach, the cost estimates differ greatly. Our total protection costs scenario for a 1-meter rise in sea level ranges from \$3.12 billion to \$9.38 billion or two to five times larger than the IPCC estimate. There are four reasons for the significant difference in cost:

1. the coastline length to be nourished;
2. the width of the active beach;
3. the loss of sand from sites of nourishment; and
4. the cost of building sea walls.

COASTLINE LENGTH

Using desktop methods, the IPCC report identifies 25 km of beach requiring nourishment on the Uruguayan coastline. In contrast, we propose 84.3 km of coastline for nourishment for the 1-meter scenario. The IPCC report instead proposed to build sea walls, which are significantly cheaper, but would destroy one of the country's main economic and environmental assets. The IPCC report does not identify which beaches were selected for nourishment.

WIDTH OF ACTIVE BEACH

The IPCC report assumed an active width of 1 km in all cases worldwide. This is unrealistic over the long time scales being considered (Stive et al., in press). Therefore, we estimated profile width based on the wave regime, as already discussed. In the high estimate, the active profile width was located up to 13 km offshore on the Atlantic Coast due to high wave energy. We believe that using a range of active widths yields more realistic calculations. However, due to the limited wave and profile data available for the study, further studies of profile width are needed.

LOSS OF SAND

Another reason for the difference in costs is our use of groins to control longshore sand losses from the nourishment projects. The IPCC methodology did not include any means of maintaining the sand in the nourishment project area. This is clearly unrealistic (Dean, 1983), and periodic renourishment or terminal structures are required to maintain the beach. We selected large terminal groins. These structures are expensive in comparison with the cost of beach fill, increasing significantly the cost of nourishment from 80 percent (0.2-meter scenario) to 40 percent (2.0-meter scenario). The costs of groins are only slightly dependent on sea level rise, while the volume of sand (and cost) is strongly dependent on sea level rise. Therefore, with increasing sea level rise, the beach fill becomes an increasing component of the cost.

COSTS OF BUILDING SEA WALLS

The two studies use different values for the cost of building sea walls to protect the coastline. The IPCC report estimates a cost of $0.72 million/km of coastline protected with a sea wall, whereas our study estimates costs ranging from $0.6 million (sheltered type of sea wall) to almost $4 million (high-estimate type sea wall for the Atlantic Coast). However, these costs differences are relatively minor when compared to those due to beach nourishment.

RESPONSES

Local and national officials must try to find a balance between losing part of the coastal zone and opting for protection. The coastal zone in Uruguay is probably the most valuable real estate in the country. It was estimated that if no action were taken, sea level rise could cause between $13 million (0.2 meters) and nearly $3 billion (2.0 meters) in infrastructure and land losses at present value. As mentioned before, these figures do not account for other impacts in the national economy, particularly the tourist industry. Protecting important areas will also be expensive. If the estimated expenditure were spread uniformly over 50 years (2050 to 2100), it would constitute 6.5–9.2 percent of the 1988 gross investment.

It is also important to clarify that all these costs were calculated as if the sea level rise occurred at the time of the survey (July 1991). The present trend of development in coastal areas can be expected to continue. Therefore, the impact of sea level rise in the year 2100 can be estimated to be even higher than the figures presented in this study. Moreover, the cost of protecting the coast will also rise due to global inflation of prices.

There has been much discussion in the scientific community on the timing of actions to prepare for sea level rise (Risbey et al, 1991; Schlesinger and Jiang, 1991). Some scientists say we should wait until better data are collected and we know more precisely the amount of future sea level rise. The purpose of this study is not to determine a sequence of steps that should be taken but to raise awareness on the vulnerability of coastal environments. It is prudent in a country like Uruguay where so much pressure is on the coastal zone to examine the long-term consequences of different development options. Many developed countries have realized the mistakes of unplanned development and growth of their coastal zone. Uruguay can learn from those mistakes and improve the quality and quantity of coastal development. As shown in this study, management measures, such as building setbacks, can prove to be effective not only to diminish vulnerability from sea level rise but also as a "smart" move to enhance the quality of coastal environments and aid their sustainable use.

NOURISHMENT

In general, we proposed nourishment for most of the coast of Uruguay, where action was necessary. We made this decision because the main use of the coast of Uruguay is for recreation and tourism, and the beaches are the main attraction. Figure 3 shows a picture of Playa Pocitos in the city of Montevideo, where highly valuable structures would be damaged or destroyed by sea level rise.

FIGURE 3. PLAYA POCITOS, CITY OF MONTEVIDEO

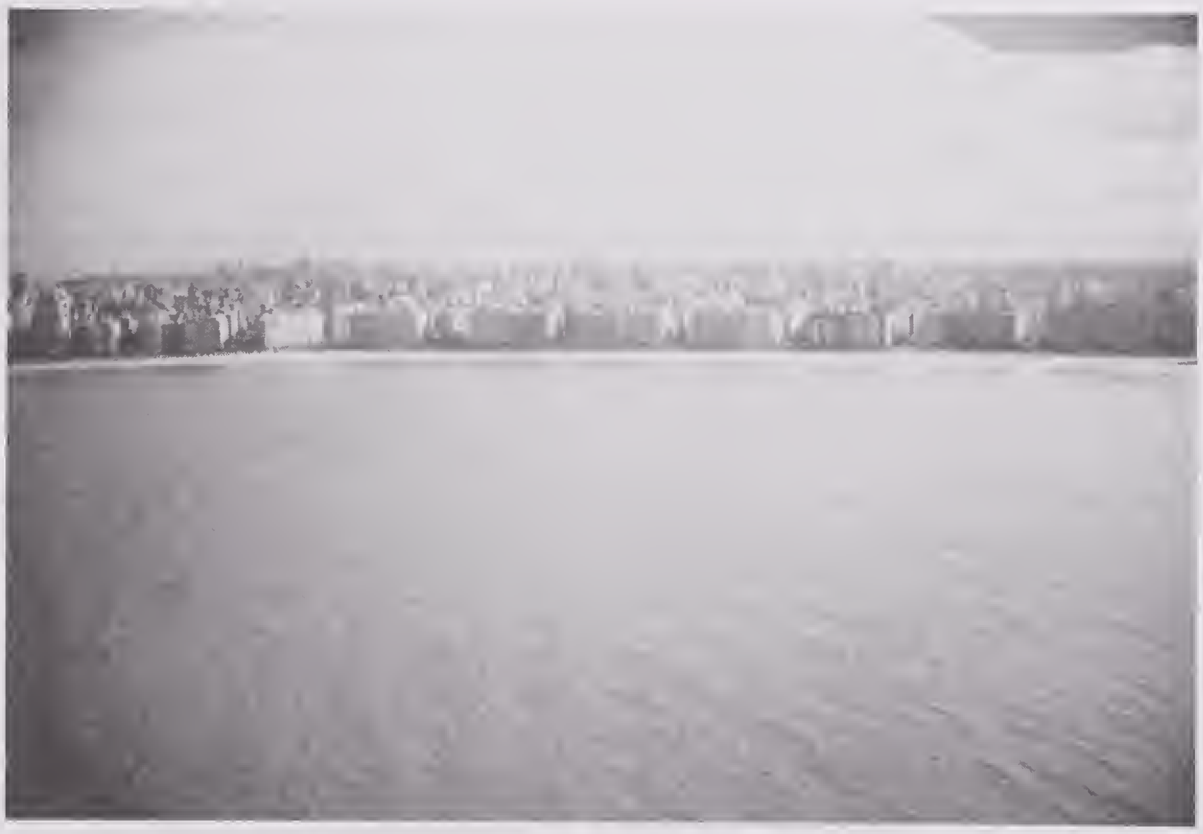

Photo by Gustavo Barrios, June 1991.

It is proposed to nourish 47–106 km (7–15 percent of the length) of the Uruguayan coast, depending on the sea level rise scenario. Specifically, we proposed nourishment for (1) urban areas where the shoreline recession will affect structures and (2) sandy beaches that have national recreational value. In Uruguay, these two criteria go hand in hand, because most coastal urban areas were established to provide services for recreational uses of the adjacent beach.

For the 0.2- and 0.5-meter scenarios, the large groins constitute 70 to 87 percent of the cost. However, under the high scenarios, the groins account for only 50 percent (1 meter) and 40 percent (2 meters) of the total cost. Therefore, for the 0.2- and 0.5-meter scenarios, other less expensive actions may be advisable, such as adding sand more frequently (renourishment) or other new technology to prevent longshore losses (Davison et al., 1992). For the 1.0- and 2.0-meter scenarios, the cost of the nourishment is almost equally divided between the sand and the groins. Therefore, beach nourishment could be substituted for groin construction. The cost of nourishment should be examined in more detail, given that some of the parameters, such as depth of closure and wave characteristics, are based on limited data.

Nourishment was proposed for most of the important coastal zones. This decision was made because of the existing recreational use of these coasts. However, the cost of beach nourishment for any given scenario is uncertain. Policies to deal with sea level rise should consider this uncertainty. Uruguay has the alternative option of building sea walls at a much lower cost. However, it has been shown all around the world that using hard structures to protect sandy beaches does not solve the problem of rising sea level and the erosion it causes (Davison et al., 1992). In fact, sea walls may even accelerate the process of the beach loss.

One of the negative aspects of nourishment projects is finding a source of sand. We estimated that Uruguay would need between 75 and 1,000 million cubic meters of sand, depending on the sea level rise scenario and active width of the profile. This can cause serious problems, because there is a finite availability of suitable material. The shortage of material readily available can escalate sand prices, along with nourishment costs (Titus et al., 1991).

SEA WALLS

Sea walls were proposed in very few cases. Besides the upgrading of existing sea walls, construction of new sea walls was proposed for three types of areas: (1) towns landward of wetlands that could be inundated, (2) low rocky/grassy headlands that are developed and would be prone to more frequent flooding, and (3) urban areas that do not have nationally recognized recreational beaches, such as some of the towns of San José and Colonia. For the first two cases, the sheltered type of sea wall was used, and for the third, low and high sea walls were assumed.

Some of these urban centers (a section of the city of Colonia (Colonia), Kiyú and part of Playa Pascual (San José), Fortín de Santa Rosa to Atlántida (Canelones), and part of La Pedrera (Rocha) are located on eroding cliffs. Thus, sea walls designed for this type of land form are proposed. In total, about 16 km of coastline falls in this type of sea wall.

DEVELOPMENT PATTERNS

Along most of the Uruguayan coast, both the natural beach width and the dune system have been maintained, even in some high-density urban areas. This reduces the vulnerability of these areas to the impacts of sea level rise. The use of building setbacks—either a legislative setback of 250 meters, required by law since the 1970's, or a de facto setback due to the presence of coastal boulevards seaward of development—allows some retreat from the shore with higher levels of the sea. When the retreat model was overlaid on urban centers, the infrastructure at risk to small rises in sea level was of limited value, illustrating the benefits of building back from the shore.

Setbacks in the development of coastal towns in Uruguay were not enforced until the late 1970's, when a 250-meter setback was made law. Undeveloped land seaward of this line has been declared public domain to maintain public ownership of the coast and to preserve this area for future generations. Beach erosion is not directly addressed, and the constant 250-meter width is not related to existing shoreline recession rates. Moreover, most of the coastal urban centers were developed before this time, so that law has had little impact on areas already developed.

However, another feature of coastal urban design helps to diminish the impact of sea level rise. Most coastal towns are developed behind a coastal boulevard that separates the first line of buildings from the water. This translates into a de facto setback of 100 to 200 meters, depending on the width of the boulevard. Examples of this are the eastern sections of the city of Montevideo and many of the coastal towns in the departments of Canelones and Maldonado (Figure 4). These setbacks limit the human impacts of sea level rise, particularly for the smaller scenarios. It was assumed in this study that no action would be taken to protect the coastal boulevards, and that their destruction would be allowed. Protection measures were only investigated when buildings were at risk. Protecting the coastal boulevards would raise the protection costs presented in this study significantly.

FIGURE 4. WEST COAST OF PENINSULA PUNTA DEL ESTE, DEPARTMENT OF MALDONADO

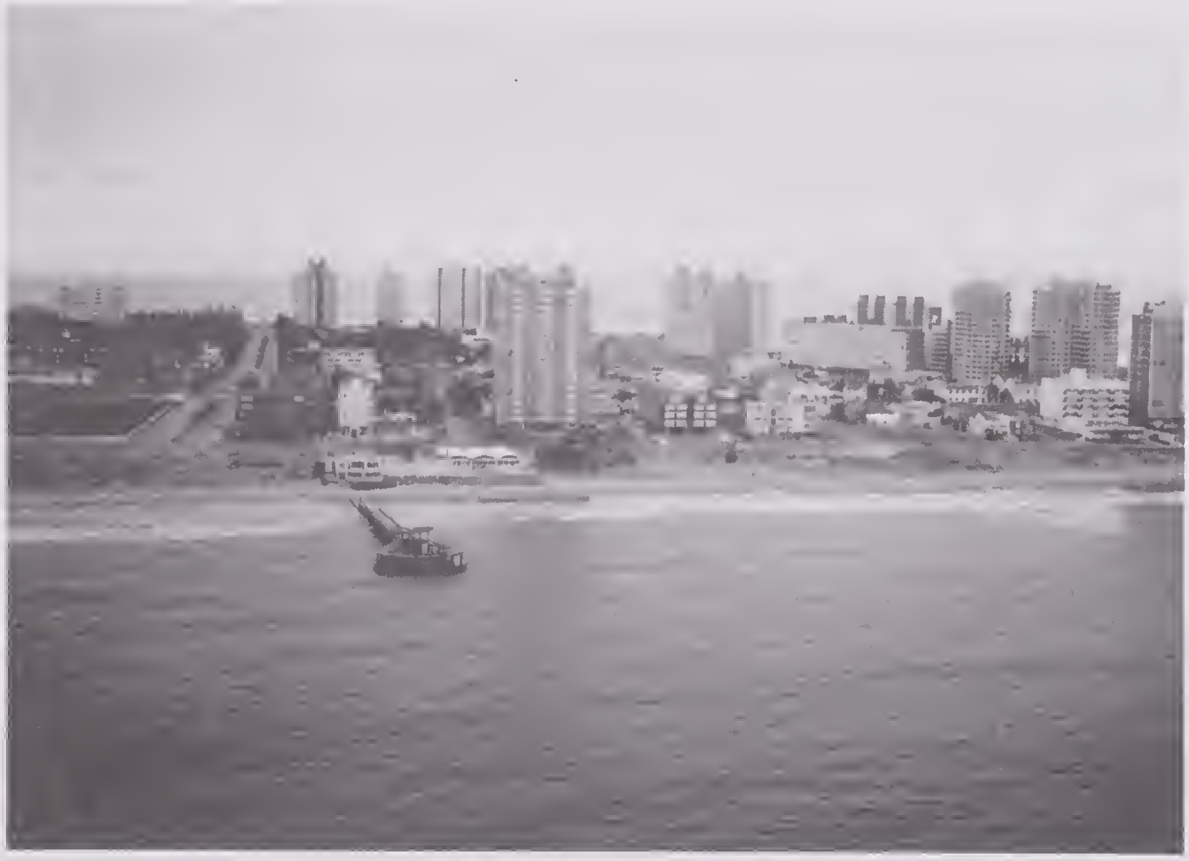

Photo by Gustavo Barrios.

FOLLOW-UP STUDIES

The lack of baseline information on coastal environments is a worldwide problem (Nicholls et al., 1992b). Uruguay needs to establish a systematic way of collecting such data. This study has provided a first assessment of the serious impacts that sea level rise could have on the Uruguayan coast. The results could be significantly improved if better base information were available. At the same time, because the Uruguayan coast is so vulnerable to sea level rise, Uruguay should take some measures to decrease this vulnerability. Following are some suggestions for such improvements:

1. Improve existing data on mean sea level. Modernize existing tidal gauges to accurately measure future trends in sea level rise.

2. Establish at least two permanent wave-recording stations, one offshore of the Atlantic coast, and another in the Río de la Plata. Offshore of Punta del Este and Montevideo could be two relatively easy locations, adjacent to sites where the value of the data could be maximized.

3. Conduct large-scale mapping of the coastal zone to improve knowledge of coastal land use and to learn what exactly could be affected by sea level rise. Regular aerophotography or satellite imagery could be one source of information that can keep updated records of the changes in land use, etc. This information could be handled within a Geographic Information System.

4. Analyze historical shoreline changes in three dimensions: in a horizontal plane by establishing erosional or accretional trends of the shore; and in the third dimension through the study of beach profiles to determine changes in sand volumes. Establish a series of stations at selected locations to have comparative records. Better understanding of historical trends could improve the methodology of studies on the impacts of sea level rise.

5. Conduct a reconnaissance survey of possible sources of suitable material for nourishment projects. The environmental and economic consequences of this approach should also be studied to determine which locations will be less harmful and economically feasible. We do not know if enough sand is available at present for the proposed nourishment.

6. Conduct further studies of some of the urban centers of the departments of Colonia and San José; impacts on marshlands; the coast east of Atlántida in the department of Canelones; the city of Piriápolis; the coast west of Punta del Este within the city limits; the growing towns of Aguas Dulces and Valizas; and the barriers of the coastal lagoons of Garzón and Rocha.

7. Establish a coastal zone management policy, as suggested by the IPCC Working Group III (1990). Even though the Uruguayan government has begun this process, speedy implementation is required.

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THE IMPACT OF SEA LEVEL RISE ON THE COASTLINE OF VENEZUELA

José Arismendi
Centro de Procesamiento Digital de Imágenes
Instituto de Ingeniería and
Ministerio del Ambiente y de los Recursos
Naturales Renovables
Caracas, Venezuela

Claudio R. Volonté
Laboratory of Coastal Research
University of Maryland
College Park, Maryland

SUMMARY

A 1-meter rise in sea level could result in the loss of nearly 6,000 km^2 of land along the Venezuelan coastline. The most serious effect by far would be the possible inundation of Venezuela's sedimentary, low-lying coastal plains and deltas, including the Orinoco Delta. Increasing erosion could also be very costly to Venezuela's oil infrastructure along the coast, and the several urban areas, which are particularly vulnerable because of the absence of setbacks. Sensitive ecosystems related to the fishing industry, such as mangroves and coral reefs, could be seriously degraded.

Nourishment of recreational beaches and construction of sea walls along the 200 km of developed coastal areas could cost about $1.5 billion. Assuming that this investment would occur over 50 years (2050 to 2100), this represents annual expenditures of 0.1 to 0.2 percent of Venezuela's gross national investment in 1987.

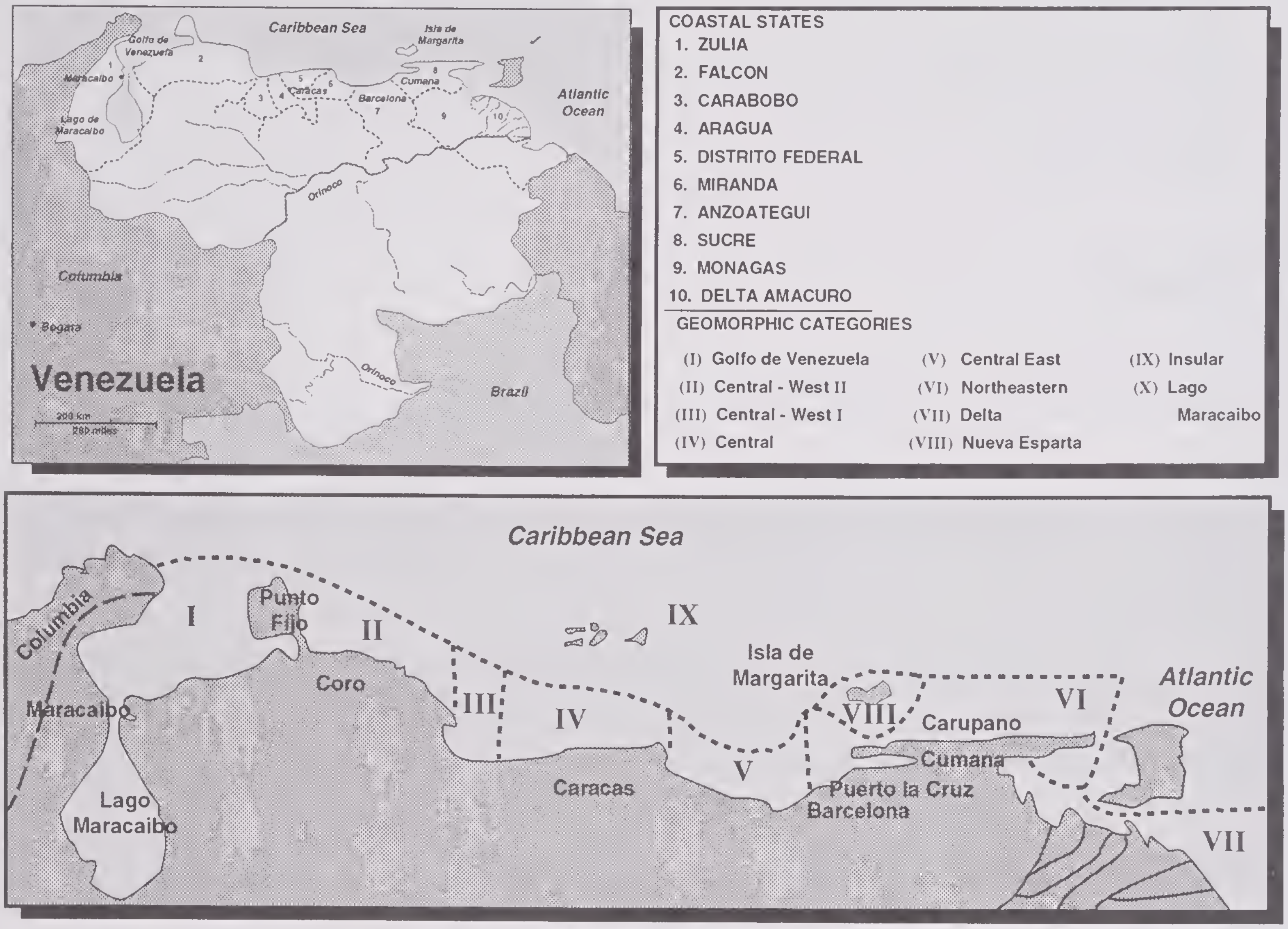
THE STUDY AREA

Venezuela's coast is about 2,875 km long, with borders on the Caribbean Sea (67 percent) and the Atlantic Ocean (33 percent). It extends from the western border with Colombia in the Goajira Peninsula to the federal territory of Delta Amacuro at the eastern border with Guyana. The Venezuelan coast also contains a number of islands, such as Margarita, Coche, Cubagua, and Archipelago Los Monjes (Figure 1).

The Venezuelan coast is very diverse. It includes high rocky coasts with high relief interrupted by small bays and pocket beaches, flat coastal plains of sedimentary origins, deltas with extensive flooding areas, sandy beaches sometimes several kilometers long, coastal lagoons, cliffs, coral islands, and mangroves. Only 385 km, or 13 percent of the total coastline is highly developed as urban centers, industrial areas, and ports. This is relatively small compared to other Caribbean countries, partly because of the limited development of the tourist industry.

Large lengths of deserted beaches, mountain slopes and flat coastal plains and agricultural land with limited human activity and low population density characterize the bulk of the coast. However, some sectors of the coast are being used intensively, such as the northern coast of Lake Maracaibo, the Punto Fijo area, the Litoral Central, Barlovento, the Puerto Píritu-Cumaná area, and the east coast of Margarita Island. Most coastal activities are related to oil extraction and processing, tourism, or fishing. All these activities make the coastal zone a very important part of the national economy.

FIGURE 1. COASTLINE OF VENEZUELA, WITH POLITICAL AND GEOMORPHIC CLASSIFICATIONS



Of Venezuela's 20 states and 3 federal territories, 9 states (Zulia, Falcón, Carabobo, Aragua, Miranda, Anzoategui, Sucre, Nueva Esparta, and Monagas) and 2 federal territories (Distrito Federal and Delta Amacuro) have coastal areas (Figure 1). The population of these federal entities comprises more than 11.7 million people, or 65 percent of Venezuela's total 1991 population (Oficina Central de Estadísticas e Información, 1991). A good portion of these people live in the coastal zone, but quantitative demographic data at this scale were unavailable for this study.

The coastal zone of the Distrito Federal (Caracas, the national capital is located about 50 km inland and 800 meters upland) presents the most developed coast in proportion to its total length. Narrow coastal plains, no more than 1 km wide, are located in front of high relief and are highly developed with tourist facilities, harbors, and industrial infrastructure.

Following a previous study by a Venezuelan coastal expert (Perez Nieto, 1986), we divided the coast into 10 geomorphic categories (Figure 1) during our analysis, but the tables are presented by state instead of geomorphic zones.

ANALYTICAL METHODS

SEA LEVEL RISE SCENARIOS

We assumed four arbitrary scenarios of eustatic sea level rise for the year 2100: 0.2 (no acceleration of present trend), 0.5, 1.0 and 2.0 meters, and present levels of coastal development. We then quantified the following for each sea level rise scenario:

1. The land at risk due to both erosion and inundation.
2. The economic value of the land and infrastructure at risk.
3. The cost of protecting the land and infrastructure.

Other consequences of sea level rise, such as saltwater intrusion, rising water tables and increased flooding, were not examined at this time.

FIELDWORK

The authors videotaped the Venezuelan coast from a small plane, conducted ground surveys, consulted with national coastal experts, and employed the Aerial Videotape-Assisted Vulnerability Analysis (Niang et al., in these proceedings; Nicholls et al, 1992). The video record provided an oblique view of the coast from which we extracted information on relative topography, geomorphology, land use, and human activities. The ground surveys gave occasional high-quality data points that, with the aid of the video record, could be interpolated along the shore.

At least one representative ground survey was obtained from each of the coastal geomorphic zones. Some of the surveys were completed in Ciudad Ojeda and Lagunilla (Lake Maracaibo) (state of Zulia), Adícora and the Isthmus of Paraguaná, Chichivirichi and Morrocoy National Park and Tucacas (state of Falcón), Puerto Cabello and Morón (state of Carabobo), Catia la Mar, Maiquetía, Guaira and Puerto Francés (Distrito Federal), Higuerote and the Barlovento area (state of Miranda), Puerto La Cruz (state of Anzoategui), Santa Fé, Playa Colorada, Mochimba, Cumaná (state of Sucre), and several locations in Isla Margarita (Figure 1).

ESTIMATES OF LAND AT RISK

We first looked at the type of land form along the coast according to our geomorphic classification (mangroves, sandy beach, cliffs, coral reef, soft or rocky headland), and its physical parameters (active length, height and width of profile). We then determined whether erosion or inundation would be the principal cause of land loss, and applied a sea level rise scenario. Table 1 presents a summary of coastline lengths by state and by type of impact for all sea level rise scenarios.

EROSION

The Bruun Rule is widely used to calculate erosion due to sea level rise. (For a description of the erosion model and the Bruun Rule, refer to Niang et al., in these proceedings.) The depth of closure is the variable in the Bruun Rule equation that is the most difficult to estimate. For the purpose of this study, we used two estimates of depth of closure—d_{L1} and d_{L100}—representing the greatest depths where intense on/offshore and alongshore transport will occur within a typical year or within 100 years, respectively. The two values give a range of estimates of land at risk due to erosion. According to our best estimates, we determined d_{L1} to be 5 meters and d_{L100} to be 8.75 meters along the entire coast.

TABLE 1. COASTAL LENGTHS BY STATE AND TYPE OF SEA LEVEL RISE IMPACT (KM)

States	Erosion	Inundation	No Impact	Total Km
Zulia (km)[1]	406.9	377.3	0.0	784.3[2]
(Percent)	*51.9*	*8.1*	*0.0*	
Falcon (km)	268.1	210.2	77.9	556.2
(Percent)	*48.2*	*37.8*	*14.0*	
Carabobo (km)	22.1	3.0	13.2	38.3
(Percent)	*57.7*	*7.8*	*34.5*	
Aragua (km)	6.6	3.8	44.4	54.7
(Percent)	*12.0*	*6.9*		*81.1*
Distrito Federal (km)	67.7	0.0	36.2	103.8
(Percent)	*65.2*	*0.0*		*34.8*
Miranda (km)	62.9	4.0	28.0	94.9
(Percent)	*66.2*	*4.2*	*29.5*	
Anzoategui (km)	54.2	6.8	3.1	63.7
(Percent)	*85.1*	*10.7*	*4.2*	
Sucre (km)	66.2	53.8	439.0	558.9
(Percent)	*11.8*	*9.6*	*78.6*	
Monagas (km)	0.0	35.0	0.0	35.0
(Percent)	*0.0*	*100.0*	*0.0*	
Delta Amacuro T. (km)	0.0	400.0	0.0	400.0
(Percent).	*0.0*	*100.0*	*0.0*	
Nueva Esparta (km)	95.7	17.9	71.7	185.4
(Percent)	*51.6*	*9.7*	*38.7*	
Total	**1,050.4**	**1,111.8**	**713.5**	**2,875.7**
(Percent)	***36.5***	***38.7***	***24.8***	***100.0***

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[1] Includes the coast of Lake Maracaibo.

INUNDATION

In case of mangroves (e.g., Delta Orinoco) or protected gulfs (e.g., Golfete de Coro), we applied a straightforward inundation, or "drowning" concept. A known contour, the 2-meter one, is marked on a map or estimated from the video, and then the distance to the water line is calculated. A constant gradient of slope is assumed, and the level of the sea (or location of water line) is raised. The new water line is calculated, and the land seaward of this land is inundated and assumed at risk. At this point we are not estimating a rate for the conversion of dry land to mangrove.

RESPONSE OPTIONS

The responses to sea level rise presented in this study range from doing nothing and letting the shoreline erode to protecting the entire coastline. This section presents four types of responses: (1) retreat or abandonment, assuming that no protection will be planned and any existing protection would not be taken into consideration; (2) upgrade of existing protection; (3) protection of only important areas of the country, mainly cities, tourist beaches, ports, and industries; and (4) protection of the entire coast with a population density greater than 10 people/km^2.

RETREAT OR ABANDONMENT

The video record provided us with information on the types and number of structures in urban centers and types of land uses along the coast. We based our price estimates of land and buildings on interviews with local real estate agents and our personal knowledge.

We did not value mangroves or coral reefs because of a lack of suitable information. This is not a reflection of their importance as a source of food and habitat for numerous animal and plant species or as flood protection for the dry land behind them (Costanza et al., 1989). For similar reasons, we did not estimate the value of industries located on the coast or include the economic value of ports that would have to be closed if they were not upgraded to new water levels.

The methodology for determining the number of structures vulnerable to the retreat option is very simple. The video record provides us with information about the distribution of structures relative to the existing shoreline. We related all new shorelines to this distribution, assumed that structures seaward of these new lines would be destroyed by a particular sea level rise scenario, and recorded their values. We assumed that the value of urban real estate is included in the value of the structure. In most cases, we assumed that the width of the existing beach would be maintained and move landward. Therefore, we added the width of the beach to the horizontal shoreline recession to determine the extent of the impact. In the case of rural land, we estimated an average value according to our sources, and then applied this value to the area estimated to be lost by the appropriate model.

UPGRADE OF EXISTING PROTECTION

Several areas and ports along the coast of Venezuela are currently protected by structures. Most of the areas that we considered that had some type of sea wall protecting their coasts were industrial or military zones. The total length of coast considered protected with sea walls in this study was 41.9 km. Therefore, in this case of protection, we have to assume that these structures will be upgraded and repaired for higher sea levels.

The industrial area of Punto Fijo, on the Península de Paraguaná, in the state of Falcón has about 4.4 km of protected coasts. On the northern coasts of Lake Maracaibo, extensive areas are protected. The city of Maracaibo and its suburbs are protected by low sea walls (10 km), and the harbor is protected by other structures (about 9 km). On the northeastern coast of the lake, the cities of Ciudad Ojeda and Lagunilla have been suffering serious subsidence problems for the last three decades due to extensive oil extraction. These two urban areas have a 20-km dike that is periodically upgraded to protect the infrastructure behind and below lake mean sea level. The state of Aragua has 3.5 km of protected coast, mainly in the Bay of Turiamo, where there is a naval base.

The coast of the Distrito Federal has several areas where extensive coastal structures have been built, mainly in the form of groins and breakwaters. Even though they may be efficient in controlling the wave energy attacking the coast, these structures do not stabilize the shoreline against sea level rise. Most of them will have to be redesigned because the new levels of the sea will overtop them. Therefore, from the point of view of this study, these areas were not considered to be protected. The only coast considered protected was the area of Arrecife, where there is industrial development along approximately 1.6 km of the coast.

The area of the Bay of Pertigalete, in the state of Anzoategui, has a cement industry with sea walls on its 950-meter waterfront. In the state of Sucre, the only area that we considered protected was the east side of the city of Cumaná, which has about 1.37 km of industrial coastline.

To calculate the cost of upgrading the sea walls, we designed three types of sea walls. We then used costs per cubic meter in Venezuela of purchasing, transporting, and placing rock (\$100/m^3) (1991 U.S. dollars), along with design (10 percent) and maintenance costs (20 percent of total cost), to calculate the cost per kilometer of sea wall. The three types of sea walls are basically a low and high estimate for open wave-exposed coasts, and a third type that is for sheltered areas. (For full description of sea wall designs, see Niang et al. in these proceedings.)

For the 0.2-meter scenario, we thought it was appropriate to only use a sheltered sea wall type to upgrade the existing sea walls. For the higher scenarios, we used low and high estimates of sea walls, when appropriate. Of the 41.9 km of existing sea walls, 8.4 km are located on open oceans, for which we calculated low and high estimates of sea walls. For the 0.2-meter scenario, we assumed that the existing sea walls could be raised; for the higher scenarios, new sea walls would have to be designed. Because one of the main parameters in the design of the high-estimate sea wall is the wave height, we decided to calculate the design of eight sea walls according to the type of wave regime. The costs of these sea walls for the 1-meter scenario of sea level rise vary from \$0.4 million (sheltered), to \$0.5 million (low estimate), to \$0.7–\$1.4 million (high estimate).

Existing ports also require protection. The most important ports, from west to east are: Maracaibo, Punto Fijo, Punta Cardón, Puerto Cabello, Palito, Puerto La Guaira, Arrecife, Puerto La Cruz, Puerto Guaraguao, Cumaná, Carúpano, Guiria, Porlamar, Chacachacore, and Pedernales. The Intergovernmental Panel on Climate Change (IPCC) Working Group III (1990) estimated the cost of protecting these ports at \$597 million for a 1-meter rise in sea level. We used this estimate since we do not have the information to improve on it. For the 0.2-meter, present trend scenario, we used a cost of \$119.40 million; for 0.5 meters, \$298.50 million; and for 2.0 meters, \$1,194 million.

PROTECTION OF IMPORTANT AREAS

This response to sea level rise is based on protecting medium to high residential development and tourist areas, plus other strategic areas, such as ports. It is considered to be the most likely protection option in the event of sea level rise. Our selection of areas to be protected under this case was based on: (1) towns or urban areas where structures would be affected by a sea level rise scenario; (2) industrial areas with possible impacts; (3) coastal roads that are considered important for communication; (4) important recreational areas; and (5) areas that already have protection (upgrade of existing protection). In the third category, we included the coastal road of the Distrito Federal, in the state of Carabobo, and the coastal road in front of San Antonio del Golfo and Playa Brava, in the state of Sucre (approximately 30 km of coastline). In the fourth category, we included such areas as Balneario Calmarechico in Zulia, Puerto Frances in Miranda, and Playa Colorada and Balneario Chacopata in Sucre.

Beach Nourishment

For most of the urban areas and all important recreational beaches, we proposed to design nourishment projects to protect the beaches from being eroded. On a national scale, about 70 km of coastline were proposed for nourishment, corresponding to the following towns and recreational beaches: Balneario Calmarechico (Zulia); Boca de Aroa, Chichivirichi, San Juan de los Cayos, Vela de Coro, Adícora, Buchuaco and El Supí (Falcón); Puerto Cabellos, and Pequivén (Carabobo); Choromí, Cata, and El Playón (Aragua); Macuto, Caraballeda, Naiguatá, Camurí Grande, Los Caracas, Catia la Mar, Oriaco, and Puerto Maya (Distrito Federal); Puerto Francés, Higuerote, Tacarigua, and Chirimena (Miranda); Lechería, and Puerto La Cruz (Anzoategui); Arapo, Playa Colorada, San Luis, and Balneario Chacopata (Sucre); and Porlamar, Pampatar, and Playa El Agua (Nueva Esparta).

We calculated the amount of sand for a nourishment project by estimating the volume of a layer of sand with the thickness of the assumed sea level rise scenario. The width of this layer goes from the first dune (including dune) or measured contour to the depth of closure. We assumed the cost of a cubic meter of sand to be $5 according to general world price. We added large groins to both ends of the nourishment project, where necessary, to preserve longshore losses. (For a full description of nourishment project designs, refer to Niang et al. in these proceedings). Not all project sites need these groins. Some pocket beaches, such as Playa El Agua on Margarita Island have natural delimiting headlands at both ends that act as groins containing the material within the length of the project. Other beaches needed only one groin because one of their limits was a headland, such as San Juan de los Cayos and Puerto La Cruz.

Hard Structures

We also estimated the cost of protecting industrial zones and coastal roads that are vulnerable to sea level rise. We considered a small number of urban areas where beaches are not used for recreational purposes but where coastal structures would be affected by sea level rise. Some examples are Uria, Punta Care, Anare, a new development near Barcelona, Cumaná and La Guardia on Margarita Island. Sheltered type sea walls were used for areas that are inside protected bays or behind mangroves or coral reefs and that are not hit directly by waves. Low and high types of sea walls were used for the rest of the cases, which are directly hit by waves. The sea wall costs already presented in the previous case were used.

TOTAL PROTECTION

The total protection case assumes that all coastal areas with more than 10 people per km^2 will be protected. This is partly to make possible comparisons with the IPCC (1990) estimates of the cost of a 1-meter rise in sea level. In the case of Venezuela, all coastal states have more than 10 people per km^2, according to a recent publication of the Oficina Central de Estadísticas e Información (1991). The federal territory of Delta Amacuro has 2.1 people per km^2; therefore, it was not considered further.

To the previous response of protecting important areas, we added approximately 1,500 km of coastline to be protected. The rest of the coast will either have no impact due to hard rock geomorphology (714 km, or 25 percent) or is part of the federal territory of Delta Amacuro (400 km, or 14 percent). Thus, the total protection case covers about 60 percent of Venezuela's coast (1,749.2 km). The 1,500 km added correspond to coastal lands that have limited human activity and, on a local scale, low population density. For about half of this coastline (780 km), which is located in protected bays and has mangroves or coral reefs, or is located in Lake Maracaibo, we decided to use a sheltered type of sea wall. We assumed that the rest (770 km) would be protected by low and high types of sea walls.

RESULTS

SHORELINE RECESSION AND LAND AT RISK

About 714 km (25 percent) of the Venezuelan coast, characterized by high-relief mountains and cliffs, will experience no serious impacts due to sea level rise (Table 1). Table 2 summarizes the total land at risk under the different scenarios. We divided inundation into two sections to show the extensiveness of the projected inundation of the deltas of the Orinoco and San Juan rivers ("inundation deltas"). This table shows that most land at risk on the Venezuelan coast will be due to inundation of low-lying areas, even if the delta zone is not included. Over 90 percent of the land at risk is due to inundation of the delta, while erosion is responsible for less than 1.5 percent of the land vulnerable for each scenario. For sea level rise scenarios of 1-meter and higher, 5,686 to 11,358 km^2 could be lost.

TABLE 2. ESTIMATED LAND AT RISK (KM^2)

	Sea Level Rise Scenarios			
Protection Strategy	*0.2 m* *Low - High*	*0.5 m* *Low - High*	*1.0 m* *Low - High*	*2.0 m* *Low -High*
Erosion	17-26	42-64	85-128	167- 248
Inundation				
Deltas	1,035	2,588	5,175	10,350
Others	86	215	426	760
Total	1,121	2,803	5,601	11,110
Total	**1,138-1,147**	**2,845-2,867**	**5,686-5,729**	**11,277-11,358**

It should be noted that the difference between d_{L1} and d_{L100} is the land at risk of being eroded. Because of the relatively small percentage of this type of land compared to the total figure, the difference between the two estimates is modest. Following are descriptions of the land at risk in specific areas along the coast.

ZULIA: GULF OF VENEZUELA

The extensive sandy beaches of the state of Zulia show recession averaging 250 meters for the 2-meter scenario. However, because this area is largely undeveloped, the societal and economic impacts could be minimal. The sandy dunes will be able to migrate landward with no major obstacles. Particular attention should be paid to the area of Castilletes, the border with Colombia, where the loss of the sandy barrier of the Laguna de Cocinetas could relocate the international boundary southward, with a net loss for Venezuela.

LAKE MARACAIBO

Lack of information on wave conditions and time constraints did not allow us to quantify the retreat model in Lake Maracaibo. A qualitative analysis can assume that because of shallow water depths and limited fetch, the wave action is minimal. Therefore, the main cause of land loss in this area would be inundation. The northern half of the lake consists mainly of sandy beaches and small cliffs that would be eroded by higher levels of waters. Along the southern part are low-lying areas and mangroves, which would suffer permanent or more frequent inundation problems.

FALCÓN: GULF OF VENEZUELA

The coast of the state of Falcón on the Gulf of Venezuela, including the Península de Paraguaná, has steep offshore gradients, reducing the net estimated erosion. The maximum recession calculated for a 2-meter rise does not exceed 250 meters. The coasts of the Golfete de Coro present serious flooding problems that could only increase with higher levels of the sea, mainly in the area of Punta Cardón and its urban area located on a low coastal area.

FALCÓN: CARIBBEAN SEA

A great portion of the east coast of the state of Falcón on the Caribbean Sea consists of high-relief cliffs. Even though some of them are eroding, the land-loss model shows very small retreats for them. Some lower river valleys and coastal plains show recession of at most 100 meters. The urban area of San Juan de los Cayos, both on a barrier and on the mainland, show extensive shoreline recession of up to 600 meters for the 2-meter scenario.

FALCÓN: MORROCOY NATIONAL PARK

The Morrocoy National Park (Figure 2) consists of a series of coral reefs and mangrove keys with very low relief (1 meter or less above mean sea level). Like any other ecosystem that depends directly on the level of the sea, Morrocoy is highly vulnerable to sea level rise. A more detailed study should be done, even though the scientific community is still studying the quantitative impacts of sea level rise on this type of ecosystem. Higher sea levels may cause greater growth of the mangroves up to a certain threshold value, after which they could drown (Ellison and Stoddart, 1991). For the purpose of this study, we assumed that with a 1-meter rise the entire park would be inundated.

FALCÓN: GOLFO TRISTE

The coast of the Golfo Triste, in the state of Falcón, is already suffering serious erosional problems in the area of Boca de Aroa. The houses in the front row have already been abandoned in recent years because the sea has started to erode their foundations (Figure 3). Behind the first row of houses a national highway could be seriously threatened by any rise in sea level. The erosion model shows shoreline recession of up to 250 meters landward for the 2-meter scenario.

FIGURE 2. MORROCOY NATIONAL PARK, STATE OF FALCÓN

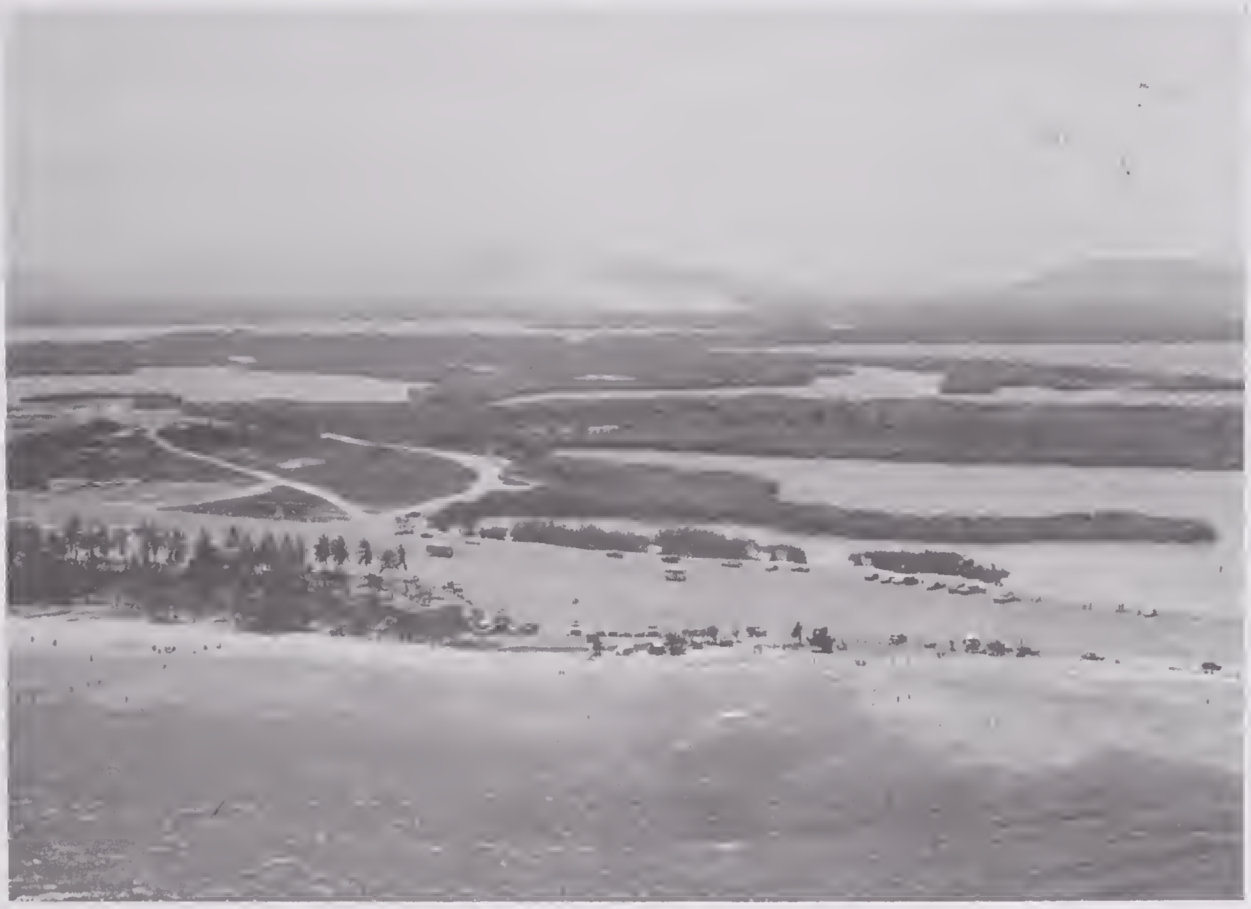

Photo by José Arismendi.

FIGURE 3. ABANDONED HOUSES SOUTH OF BOCA DE AROA, STATE OF FALCÓN

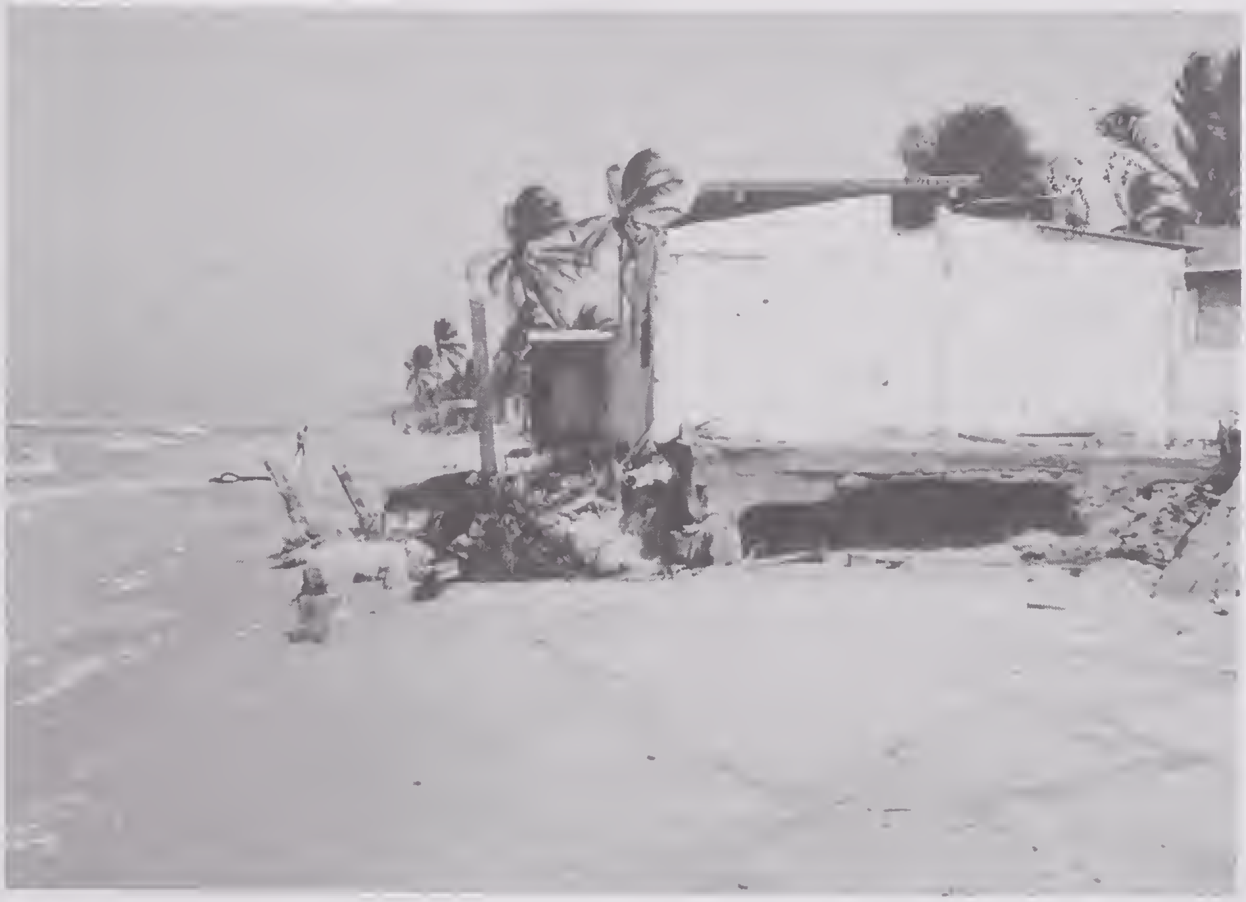

Photo by Claudio R. Volonté.

CARABOBO TO ARAGUA

Starting in the state of Carabobo and continuing west in the state of Aragua, the high-relief mountains get closer to the Caribbean, reducing the coastal plain to a narrow strip about 2 km wide. This area presents more serious impacts for the high scenarios of sea level rise, with shoreline recessions of up to 100 meters. The most vulnerable areas are the low coasts of several of the bays, such as Playa Blanca and Quizantal, Ocumare, and Turiamo. For tourist areas with steep offshore gradients, such as Cata and El Playón, the Bruun Rule predicts minimal landward movement of the shore.

DISTRITO FEDERAL

The high-relief coast of the Distrito Federal has a very narrow coastal plain, no wider than 1 km, and several pocket beaches. The offshore gradients are also steep. The land loss model shows landward movement of the shore of up to 100 meters. Because of the narrow coastal plain, the urban development is very close to high water and vulnerable to even small increments of sea level rise. In tourist areas, such as Caraballeda, Naiguatá, Camurí Grande and Los Caracas, a 1-meter rise could destroy the front row of houses. Most of these areas are protected by groins and offshore breakwaters that, even though partly efficient today, would have to be upgraded for higher sea levels and waves.

MIRANDA

The state of Miranda has a low coast of sandy beaches. Higuerote, its main coastal town, is developed very close to the water line, with narrow beaches (maximum 20 meters wide). A rise of 1 meter or higher could move the shoreline 170 meters landward, causing losses of valuable waterfront real estate. The area of Laguna Tacarigua and its barrier are also very vulnerable, even though the model shows recession of less than 100 meters. This is because the active profile is only about 400 meters wide.

ANZOATEGUI

The western part of the state of Anzoategui is very similar to Miranda, comprised of coastal lagoons, barriers, and coastal plains. A series of towns, such as Boca de Uchire and El Hatillo, could be threatened by receding shorelines. The narrow barriers are already subdivided into lots for urban expansion. This area should carefully consider the possible impacts of sea level rise on these fragile coastal environments. The model shows a shoreline movement of up to 150 meters landward, which could erode a significant portion of the planned lots.

Next, travelling east, we find another very vulnerable area between the suburbs of Barcelona, Lechería, and a new development east of Lechería (Figure 4). The suburbs of Barcelona, near the airport, are built on very low land that could be inundated permanently if no protection is built, even for the 0.5-meter scenario. Lechería is developed on a low, flat, narrow tombolo that, according to our model, will be breached by sea levels higher than 1 meter. East of Lechería is a new area developed on a flat coast, very near existing sea level (Figure 4). A 2-meter scenario could move the shoreline 2 km inland, inundating most of the development.

FIGURE 4. NEW DEVELOPMENT EAST OF LECHERÍA, STATE OF ANZOATEGUI

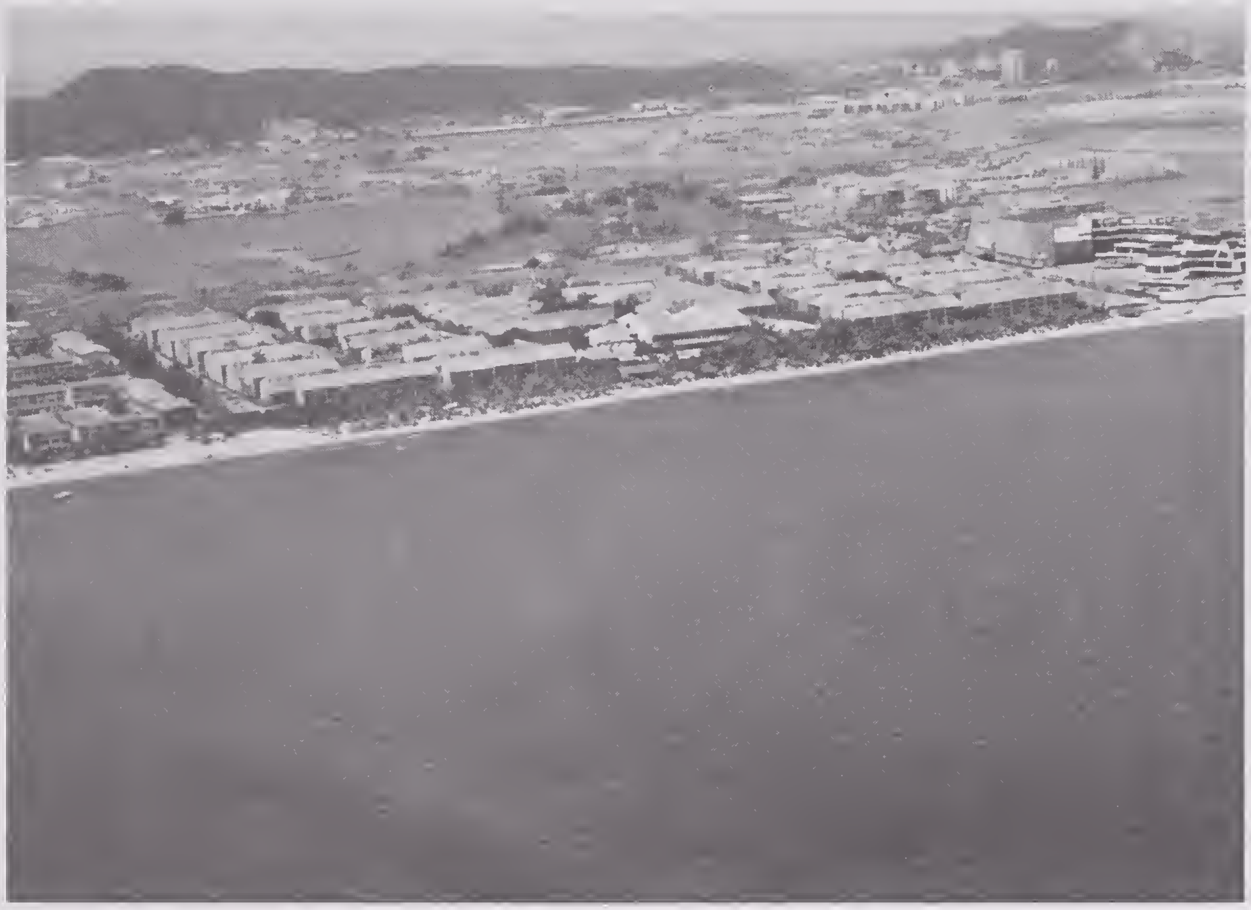

Photo by José Arismendi.

East of Puerto La Cruz, the mountain range is very close to the shoreline, leaving narrow coastal plains or pocket beaches for development. Under the 1-meter scenario, the shoreline of Puerto La Cruz could recede by 100–150 meters, destroying structures (mainly commercial) just across the street from Paseo Colón.

SUCRE: CUMAN AND GULF OF CARIACÓ

The state of Sucre has an extensive coastline, most of which will not suffer major impacts from sea level rise because of its high, rocky relief (Table 1). One of the areas most vulnerable to sea level rise would be the town of Cumaná, which is built on the delta fan of the Manzanares River. Our model shows shoreline recession of up to 500 meters for the 2-meter scenario.

The Gulf of Cariacó has very high reliefs on both the southern and northern coasts. Along the southern coast is a line of residential development, practically at sea level. These houses are threatened even today by small storm surges. A permanent rise in sea level would inundate and erode most of the narrow coastal strip. The eastern coast of the gulf is very low, with mangroves and flooded areas; small towns could be flooded permanently.

SUCRE: PENÍNSULA DE ARAYA AND PARIA

The Península de Araya is comprised of a low coast, with scattered fishing towns and salt pans. The area of Punta de Araya, with coasts on two sides of the tip of the peninsula should be the most vulnerable. Landward movement of the shore of up to 500 meters could be expected in this area for a rise of 1 meter or more. The rest of the Península de Araya and Paria (along the northern coast) consists of high-relief coasts and is practically undeveloped. Carúpano is the largest town in this area, and most of it is located at high elevations landward of cliffs. Small pocket beaches could be threatened because higher sea levels would totally erode the limited quantities of sand. Deep offshore waters diminish the estimates of land at risk.

The south coast of the Península de Paria, on the Gulf of Paria, has a series of fishing towns largely located in low coastal areas. The most important town is Guiria, with its urban development practically at sea level. Small increases in sea level rise could cause serious impacts.

MONAGUAS AND DELTA AMACURO

The coasts of the state of Monagas and the federal territory of Delta Amacuro are very similar, with very limited development. Both of them have deltaic formations with very compact mangrove vegetation. The two main rivers in these areas are the San Juan and the Orinoco. For this study we assumed that inundation would be the driving force of shoreline retreat. We estimated that a 2-meter rise in sea level would inundate an area of about 10,350 km^2, moving the shoreline about 25 km landward.

It is important to recognize that our approach is very simplistic. First, we do not know if these deltaic areas are currently eroding. Second, the changes in climate that could accelerate the rise of sea level could also change the weather patterns in the watershed of both of these rivers. These changes could result in less (or more) rainfall and less (or more) sediment to erode downstream, increasing (or diminishing) the effects of sea level rise. A more detailed study should be conducted in this area, focusing on the watershed as a whole and including the possible impacts of climate change and the impacts of human activities, such as dam construction, on sediment supply.

NUEVA ESPARTA: MARGARITA ISLAND

On Margarita Island, in the state of Nueva Esparta, coastal tourism is one of the major industries. About 20 percent of the coastline is developed for urban centers, industries, or ports. More than 40 percent of the island's total coastline will not suffer major impacts because of high-relief or cliffed coasts (Table 1). Although inundation can occur on the middle low portion (a tombolo) that joins the two original islands, erosion would cause the majority of the land loss. The highly developed area of Porlamar could suffer shoreline retreats of up to 200 meters, mainly in the hotel district. Another vulnerable area is the town of La Guardia built on the beginning of the Laguna de la Restinga on a low coastal area. Part of this town is already protected by riprap.

ECONOMIC VALUE OF LAND AND STRUCTURES AT RISK

Table 3 summarizes the economic value of structures and land vulnerable to different scenarios of sea level rise for Venezuela's states. At a national scale, we estimated this economic value to range from $111.2 to $463.6 million, depending on the sea level rise scenario. It is clear from this table and not very surprising that structural values are higher than land values on a national scale. Adding the value of mangroves, industries, and harbors would better indicate the actual economic value of the impact of sea level rise. To obtain an even more realistic estimate, we need to introduce the ramifications of those losses to the national economy, such as the impact of closing coastal oil refineries or oil pipes, losses of tourist revenues, and jobs related to those activities. Therefore, a straight benefit-cost analysis using the figures shown in Table 3 would be misleading.

TABLE 3. ECONOMIC VALUE OF STRUCTURES AND LAND VULNERABLE TO SEA LEVEL RISE (MILLIONS OF U.S. DOLLARS)

	Sea Level Rise Scenarios			
States	*0.2 m*	*0.5 m*	*1.0 m*	*2.0 m*
Zulia	NV	NV	NV	NV
Falcón				
Structures	$14	$15	$25	$27
Rural Land	NV	NV	NV	NV
Roads	NV	NV	NV	NV
Total	***14***	***15***	***25***	***27***
Carabobo				
Structures	0	3	3	3
Rural Land	1	2	5	9
Roads	0.4	0.4	0.4	0.4
Total	***1.4***	***5.4***	***8.4***	***12.4***
Aragua	NV	NV	NV	NV
Distrito Federal				
Structures	0	2	49	108
Rural Land	NV	NV	NV	NV
Roads	7	7	7	7
Total	***7***	***9***	***56***	***115***
Miranda				
Structures	0.7	7.9	9.1	11.7
Rural Land	0.1	0.1	0.2	0.4
Roads	0	0	0	0
Total	***0.8***	***8.0***	***9.3***	***12.1***
Anzoategui				
Structures	77	146	177	178
Rural Land	0.1	0.2	0.4	1
Roads	0	0	0	0
Total	***77.1***	***146.2***	***177.4***	***179***
Sucre				
Structures	1.4	1.5	8.5	9.1
Rural Land	0	0.1	0.2	0.3
Roads	0.5	0.5	0.5	0.5
Total	***1.9***	***2.1***	***9.2***	***9.9***
Monagas	NV	NV	NV	NV
Delta Amacuro	NV	NV	NV	NV
Nueva Esparta				
Structures	0.7	16	18	18
Rural Land	8.3	22.7	45.3	90.2
Roads	NV	NV	NV	NV
Total	***9.0***	***38.7***	***63.7***	***108.2***
TOTAL	**$111.2**	**$224.4**	**$348.6**	**$463.6**

The value of the road was estimated to be 15 million Bolivares per km (or $0.24 million).
NV: No value available.

At the state level, Anzoategui experiences the largest losses, even for low scenarios of sea level rise—more specifically, the urban centers of Lechería. Higher scenarios of sea level rise can cause problems in other states, such as Distrito Federal and its highly developed coast, Nueva Esparta, and Falcón. For Nueva Esparta the land lost is estimated to be much more valuable than the structures lost. Also, the losses for the 1-meter and lower scenarios are relatively high when compared to the 2-meter scenario. This is largely attributed to the linear development of structures along the coast. After the land retreats a certain distance, few structures remain to be destroyed.

UPGRADE OF EXISTING PROTECTION

Table 4 summarizes the total cost required to upgrade the presently protected coast. The low and high estimates refer to the low and high types of sea wall.

TABLE 4. ESTIMATED COSTS OF UPGRADING EXISTING PROTECTION (MILLIONS OF U.S. DOLLARS)

	Sea Level Rise Scenarios			
	0.2 m	*0.5 m*	*1.0 m*	*2.0 m*
Harbors (30.9 km)	$119.4	$298.5	$597.0	$1,194.0
Sea Wall (41.9 km)				
Low Estimate	NA	6.6	17.7	53.8
High Estimate	NA	9.2	20.5	56.0
Total	$121.4			
Low Estimate	NA	305.1	614.8	1,247.8
High Estimate	NA	307.7	617.6	1,250.0

NA: Not applicable.

PROTECTION OF IMPORTANT AREAS

Table 5 shows the estimated cost of protecting Venezuela's important coastal areas, including the cost of upgrading existing protection. The two estimates are presented corresponding to the low and high estimates of sea walls and d_{L1} (low) and d_{L100} (high) for nourishment projects. There is an increase of 40 percent between the cost of upgrading the existing infrastructure and the cost of protecting the important areas. This is mainly due to the very extensive and expensive-to-upgrade harbor facilities. Only about 160 km (or 7 percent) of Venezuela's coastline was considered important enough to be protected in this case. More than 60 percent of the cost for the 0.5-, 1-, and 2-meter scenarios is for upgrading of the port infrastructure. The nourishment projects would cost from $130 to almost $1,400 million, depending on the sea level rise scenario and depth of closure. These figures are relatively low, due to the steep offshore gradients, but still correspond to a third of the total cost for d_{L1} and d_{L100}. The limited length of new proposed sea walls does not account for much in the overall national cost of this type of protection.

TABLE 5. ESTIMATED COSTS OF PROTECTING IMPORTANT AREAS (MILLIONS OF U.S. DOLLARS)

Protection Strategy	Sea Level Rise Scenarios *0.2 m*	*0.5 m*	*1.0 m*	*2.0 m*
Upgrade Existing Protection [1]	$121.4			
Low Estimate	NA	$305.1	$614.8	$1,247.8
High Estimate	NA	307.7	617.6	1,250.0
Sea Walls (57.2 km)				
Low Estimate	3.0	9.5	25.7	78.2
High Estimate	8.9	16.5	33.0	83.2
Nourishment (70.5 km)				
Low Estimate	130.7	139.2	358.6	594.7
High Estimate	498.6	635.9	865.9	1,328.9
Total (200.4 km)				
Low Estimate	$255.1	$453.8	$999.1	$1,920.7
High Estimate	628.9	960.2	1,516.5	2,662.1

NA: Not applicable.

[1] See Table 4 for breakdown of costs.

[2] Low estimate (D_{L1}) and high estimate (D_{L100}).

TOTAL PROTECTION

Table 6 presents the calculations for protecting the entire coast of Venezuela. The total cost ranges from $338 to $5,172 million, depending on the sea level rise scenario, the type of sea wall used, and the depth of closure. The additional sea walls for total protection raise the cost of protection by a factor of two in the worst case, when compared to the most important areas protection case. Beach nourishment and harbor protection remain a large proportion of the costs.

TABLE 6. ESTIMATED COSTS OF PROTECTING THE ENTIRE COAST (MILLIONS OF U.S. DOLLARS)

Protection Strategy	Sea Level Rise Scenarios *0.2 m*	*0.5 m*	*1.0 m*	*2.0 m*
Protection of Important Areas [1]				
Low Estimate	$255.1	$453.8	$999.1	$1,920.7
High Estimate	628 9	960.2	1,516.5	2,662.1
Sea Walls (1,548.7 km)				
Low Estimate	83.2	264.7	718.1	2,191.0
High Estimate	448.8	653.0	1,117.2	2,510.1
Total (1,749.2 km)				
Low Estimate	$338.3	$718.5	$1,717.2	$4,111.7
High Estimate	1,077.7	1,613.2	2,633.7	5,172.2

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[1] See Table 5 for breakdown of costs.

[2] Low estimate (d_{L1}) and high estimate (d_{L100}).

WETLAND LOSS

The responses to sea level rise presented in previous pages considered the protection of wetland areas by building sea walls. This should be taken as a low estimate of the actual cost of protecting wetland areas. Another strategy to combat wetland loss due to inundation is wetland nourishment. Simply put, the whole wetland area at risk is raised the same amount as the rise in sea level. Thus, the amount of material required is easily calculated from the earlier inundation estimates (Table 1). A very rough cost for this procedure can be determined using the price of beach fill ($\$5/m^3$). This value probably understates the true cost of wetland nourishment, given the logistical problems of delivering sediment to these ecosystems without destroying them. The results are given in Table 7. These figures do not account for the possible wetland loss along the coastline of Lake Maracaibo.

TABLE 7. APPROXIMATE COSTS OF WETLAND NOURISHMENT (MILLIONS OF U.S. DOLLARS)

	Sea Level Rise Scenarios			
	0.2 m	*0.5 m*	*1.0 m*	*2.0 m*
Potential Land Loss from Inundation	1,121	2,803	5,601	11,110
Cost of Protecting Land with Nourishment	1,121	7,007.5	28,005	111,100

Not surprisingly, given the large areas inundated, these numbers are rather large, ranging from \$1 billion to \$111 billion for the 2-meter scenario. Clearly, wetland nourishment would be prohibitively expensive, even for small areas, unless the cost of the procedure can be significantly reduced, probably by two orders of magnitude.

COMPARISON WITH IPCC REPORT

The IPCC (1990) produced a worldwide estimate of the cost of protecting the coast for a 1-meter rise in sea level using desktop methods. The IPCC did this on a country-by-country basis by estimating the cost of protecting all the low-lying coastlines with a population of over 10 people per km^2. The low-lying coast includes all the estuaries and lower reaches of rivers that would be affected by sea level rise.

The IPCC report estimates the cost of protecting Venezuela at \$3.155 billion for a 1-meter rise in sea level. This includes upgrading harbors, protecting low coasts and coastal cities, and nourishing sandy beaches. The IPCC's methods and procedures are compatible with our total protection scenario. Even though the two studies have a similar approach, the cost estimates differ significantly. Our total protection scenario for a 1-meter rise ranges from \$1.72 to \$2.63 billion, which is about 50 to 30 percent less than the IPCC's estimates.

It is not clear whether the IPCC report included Lake Maracaibo in its calculations. If it did, the extent of the proposed sea walls for the total protection case in both studies is similar (1,500 km). If it did not, IPCC is protecting coastlines that we are not, because out of the 1,500 km in our study, 400 km correspond to Lake Maracaibo. It is also important to notice that the average price of sea walls per km used in both studies is different. We used values ranging from \$0.49 to \$0.87

million per km, compared to $1.2 million per km in the IPCC study. This is to be expected, since our design uses a smaller cross-sectional area of sea wall than the IPCC study.

Another important difference is that the IPCC report proposed building sea walls along most of the coastal cities (31 km) at an average price of $20 million per km, or a total of $620 million. Most of the cities in our report are protected by nourishment projects because they are recreational beaches. The cost of this nourishment is approximately $360 million, which is half the cost of the IPCC report. In the case of Venezuela, beach nourishment is relatively cheap because of the relatively narrow width of active beach.

APPROPRIATE RESPONSES

When the entire coast of Venezuela is considered, we see that a moderate rise in sea level will affect the developed areas along about 13 percent of Venezuela's coast. The cost of protecting the very expensive and impressive harbors could be as much as $1 billion, depending on the level of protection applied. Nourishment projects to protect recreational beaches and tourist towns could exceed the half billion dollar mark. If sea walls are proposed to protect about 1,000 km of the Venezuelan coastline, the cost could exceed $1 billion.

All these calculations were done assuming present patterns of coastal development. The present tendency for increased development of coastal areas is expected to continue. Therefore, the protection in the year 2100 can be estimated to be even greater than the figures presented in this study.

Geomorphologically, long lengths of the Venezuelan coastline are not very vulnerable to sea level rise, because they are characterized by steep coastal slopes. When the deltaic and sedimentary coastal plains are examined, the vulnerability increases. These more vulnerable areas include the deltas of the Orinoco and San Juan rivers and the coasts of the state of Falcón, mainly the Península de Pariguaná. For high scenarios of sea level rise (equal to or greater than 1 meter), the consequences could be catastrophic, measuring between 5,686 and 11,358 km^2 of land lost.

The most sensitive areas to sea level rise would be the Golfete de Coro, Morrocoy National Park, the coast between Tucacas and Moron (Golfo Triste), and urban areas of the Distrito Federal, the Barlovento area, Anzoategui, and Sucre.

The coast of Lake Maracaibo is suffering from serious subsidence problems, mainly in the areas of Lagunilla and Ciudad Ojeda, due to exploitation of oil. Global sea level rise would also increase the water levels of Lake Maracaibo. Controlling the increasing development of the lake's coast would not be economically feasible for the country's economy.

BUILDING SETBACKS

Urban areas are developed with no apparent building setbacks. This is the case for the urban centers of the Litoral Central, Lechería, Puerto La Cruz, Cumaná, Guiria, and Porlamar, which are practically built on the high-water mark, leaving no room for future retreat from the sea. All these areas, even where the retreat model estimates small landward changes in the shoreline, could experience serious losses or could require expensive defense with higher sea levels. Thus, building setbacks should be considered as a management technique.

COASTAL ZONE MANAGEMENT

A coastal zone management policy should be established, as suggested by the IPCC Working Group III (1990). A first step in developing an awareness of sea level rise is to encourage new projects on the coast to include a section treating possible impacts of sea level rise.

FOLLOW-UP STUDIES

The lack of baseline information on coastal environments is not limited to Venezuela, but is a worldwide problem. A first step to improving this situation could be the development of a systematic approach to collecting data. This study has provided a first assessment of the possible impacts that sea level rise could have on the Venezuelan coast. Although no further national assessment is recommended, the following suggested studies could greatly improve the situation:

- Large-scale mapping of the coastal zone would provide more detailed information on its vulnerability to sea level rise.

- Historical shoreline analysis would improve the understanding of the Venezuelan coastline and would assist in predicting future changes with or without sea level rise.

- International issues that could spark border conflicts should be examined, such as issues with the border with Colombia (the area of Castilletes), and the island of Ave (Aparicio-Castro and Perdomo, 1990).

- Areas that should be studied in more detail are the urban area of Punto Fijo, Morrocoy National Park, the urban strip between Tucacas and Morón, Catia la Mar to Naiguatá (Distrito Federal), Higuerote, Lechería, and Cumaná.

- Other areas that should be studied in conjunction with other climate change parameters and future development are the watersheds of Lake Maracaibo, and the Orinoco and San Juan rivers. The possible problems of landslides in the coastal zone, given the steep slopes and the possibility of increased rainfall, should be considered.

- The costs of adapting the harbors to higher sea levels should be quantified more precisely, as this appears to be a significant portion of Venezuela's protection costs.

- More research is needed on the role of wetlands in coastal resource availability, particularly fisheries, so that more rational policies on preservation can be formulated. We have not considered the role of wetlands in coastal resources, particularly fisheries. In a rather different setting, Costanza et al. (1989) have demonstrated that the wetlands of Louisiana may have a very large value. Similar assessments would be useful in the context of Venezuela, so that rational decisions concerning strategies for maximum preservation of wetlands are taken in the context of accelerated sea level rise.

- In the same context, studies of coral reefs would also be very useful to Venezuela and to many other tropical countries as well.

CONCLUSION

Much debate still exists among the scientific community about the exact amount and time of future sea level rise (Risbey et al., 1991; Schlesinger and Jiang, 1991). This report has tried to provide the Venezuelan government and scientific community with a first look at the vulnerability of their coast, as well as a series of techniques to be applied in later studies. Many of the parameters used can provoke many discussions about their precision or value. One of the most important aspects of this report should be the debate about sea level rise and its possible impacts.

This report should not be taken as a cause for alarm or complacency. The results do not represent a basis for individual waterfront owners to be concerned about a particular retreat calculation. The intention of this report was to recognize, on a national scale, the most vulnerable areas of the country. It is up to state and federal officials to evaluate their risks and proceed with more detailed studies of the areas we suggested.

We should remember that most of all that coastal environments are dynamic. Therefore, they will change, even when man tries to stop it. The higher predictions of future sea level rise are expected for the next century. Thus, we have some time to act. A first step that we can take is to start raising awareness about coastal issues. Once we start discussing the coast and try to enhance the quality of coastal development, the topic of future sea level rise will have to be raised.

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GESTIÓN DE COSTAS EN VENEZUELA

Coastal Management In Venezuela

Ernesto Díaz Velázquez
MARNR
Caracas, Venezuela

ABSTRACT

This paper analyzes the problems that affect the coastal environment from a point of view of integrated planning and institutional development. It evaluates the natural processes and functional interrelationships that take place in the coastal zone and its different components: sea, land, air, and anthropogenic activities. It also analyzes several coastal management strategies and types of institutional relationships to adequately administer coastal and marine resources. The conclusion proposes changes in the traditional decision-making processes by introducing increased citizen and local government participation within the planning and administration processes.

SINTESIS

La ponencia examina los problemas que afectan al medio costero, bajo la perspectiva de la planificación integrada y del desarrollo institucional. Evalúa los procesos naturales y las interrelaciones funcionales que toman lugar en estos espacios, entre los diferentes componentes que actúan sobre el medio costero: marino, atmosférico, terrestre y antrópico. Analiza una serie de estratégias de gestión de costas y tipos de relaciones institucionales para un manejo adecuado de las áreas y de los recursos marinos y costeros. Finalmente, propone un cambio en el proceso tradicional de toma de decisiones, en el cual aumente la participación ciudadana y de los municipios en los procesos de planificación y administración de las áreas y recursos costeros.

INTRODUCCIÓN

La costa constituye uno de los sistemas mas dinámicos y cambiantes de la tierra. En ella interactúan elementos marinos, terrestres, atmosféricos y antrópicos que determinan su forma y posición, así como las potencialidades y restricciones para su uso. Estos elementos deben ser tomados en cuenta antes y durantelos procesos de ocupación espacial y de aprovechamiento de los recursos naturales, con el fin de garantizar las posibilidades de un desarrollo ambientalmente sustenable de las regiones costeras.

Las áreas costeras albergan una gran proporción de la población mundial, la cual aumenta—aproximadamente—en 100 millones de habitantes por año, demandando, cada vez más, espacio para el desarrollode sus actividades y ejerciendo, asimismo, una creciente presión sobre los recursos naturales (PNUMA, Programa de Mares Regionales, 1990).

En Venezuela, aproximadamente 90% de la población se localiza en un 10% del territorio, al norte del Orinoco. La Región Centro-Norte-Costera, por su parte, concentra el 38% de la población, 75% de los establecimientos industriales, 57% del valor agregado, 61% del valor de la producción bruta, y 40% del capital fijo del país, en sólo 2% del territorio nacional (CNOT, Plan Nacionalde Ordenación del Territorio, 1988).

En la actualidad, Venezuela enfrenta una difícil situación económica. Como consecuencia de ésta, se han producido una serie de ajustes macroeconómicos y estructurales que exigen, asimismo, transformaciones y reformas de las instituciones. Se reconoce, especialmente, la necesidad de que se propulsen mecanismos efectivos de coordinación entre las instituciones del sector público con el objeto de atacar los problemas políticos, jurídcos, y administrativos del Estado.

Paralelamente, el lineamiento fundamental del VIII Plan de la Nación, en materia de competitividad internacional, consiste en integrar a Venezuela al mercado mundial através de una reforma radical de la infraestructura productiva y la utilización de las ventajas comparativas que ofrece el país. Sin embargo y a pesar de las ventajas comparativas que ofrecen otras regiones del país, las áreas costeras continuan siendo objeto de las mayores presiones, por diferentes usos. Esto demuestra claramente, la histórica vocación costera venezolana.

Estos antecedentes son indicadores de que debe existir una toma de decisión, al más alto nivel, preferiblemente por decisión del Congreso, para garantizar el desarrollo sustenable de las áreas y recursos costeros.

PROBLEMAS DE LOS AMBIENTES COSTEROS

La imagen que se proyecta al referirnos al término "costero" varía considerablemente deacuerdo a la auditorio ante el cual se utilice. Paraunos se refiere a espacios para la recreación y el turismo y para otros, a la pesca, a las playas, a los puertos o a los manglares, entre otros. Sin embargo, la mayoría relaciona el término con doselementos: mar y tierra.

Una—muy completa—definición de área costera combina consideraciones de tipo demográfico, funcional, ecológico, y geográfico:

La costa es la franja de tierra y el espacio oceánico adyacente, incluyendo el fondo marino, en la cual los procesos y usos terrestres afectan la ecología marina y viceversa. Funcionalmente, es una zona de amplia interfase entre tierra y mar, donde ocurren procesos de producción, consumo e intercambio, con altos niveles de intensidad. Ecológicamente, es un área de actividad biogeoquímica con capacidad limitada para sostener actividades humanas. Geográficamente, es dificil precisar los límites de la costa, pues los procesos oceánicos afectan el clima de regiones continentales lejanas a la línea costera, asi como, actividades desarrolladas en las cuencas altas tienen influencia sobre los espacios y recursos marinos; es decir que la costa es una franja de ancho variable entre dos dominios: el terrestre y el oceánico.

Los principales conflictos de uso en las áreas costeras están vinculados al desarrollo de las siguientes actividades:

- Urbanismo
- Turismo y Recreación
- Industria
- Agricultura
  - Vegetal (y forestal, en particular)
  - Pesca
  - Acuicultura
- Transporte (marítimo y terrestre)

Existen, igualmente, procesos y riesgos naturales considerados problemas costeros debido a que afectan, o podrían afectar, negativamente vidas y salud humana, así como propiedades. Tales casos, se refieren, entre otros, a deslizamientos, erosión y desbordamientos de ríos o inundaciones. La detección de la existencia de tales riesgos y la actuación oportuna de los entes competentes del Estado, contribuireía, de manera significativa, a evitar la pérdida de vidas humanas y a la minimización de los daños materiales.

A estos riesgos naturales se añaden los riesgos asociados al incremento del nivel del mar, a sismos, huracanes y tormentas, entre otros.

Los problemas asociados a la intervención humana de los espacios y recursos costeros se reflejan en la degradación de los recursos natúrales, la disminución de la calidad de las aguas y en la pérdida devalores escénico-paisajísticos, por ejemplo.

Con el fin de determinar el valor de los recursos costeros, éstos pueden ser clasificados de diferentes maneras, existiendo, siempre, los problemas relativos a la cuantificación y a la expresión de ese valor. Una clasificación propuesta, es la siguiente:

- *Recursos Marinos:* aguas marinas, humedales, vida marina: algas, corales, peces, etc.

- *Recursos Terrestres:* cuencas costeras, aguas dulces, dunas vida silvestre, etc.

- *Recursos Para la Producción*: áreas con potencial salinero, camaronero, forestal, minero, petrolero, etc.

- *Recursos de Orígen Antrópico*: ciudades, comunidades, obras de infraestructura costera, playas artificiales, valores arquitecténicos, etc.

- *Recursos Histórico-Culturales:* recursos especiales asociados a las costumbres, religiones y a la organización espacial y social de las comunidades costeras pasadas y presentes.

- *Recursos Turístico-Recreacionales:* playas, rutas escénicas, sitios para submarinismorios, etc.

- *Recursos Científico-Educacionales*: refugios de fauna, áreas especiales como habitats de especies amenazadas o en peligro, manglares, corales, etc.

Los diferentes usos de los espacios y recursos costeros involucran una serie de actividades desarrolladas por el hombre que producen cambios ambientales y socioeconómicos, tanto positivos como negativos que pueden ser reflejados, a través de relaciones causa-efecto, utilizando la siguiente secuencia. Algunos ejemplos de estas relaciones son:

Uso/Actividad	**Cambio Ambiental**	**Impacto Socioeconomico**
Urbano/Descarga de Efluentes Domésticos (sin tratar)	Contaminación de Playas	• Disminución del Valor Recreacional del Area • Disminución del Ingreso de Divisas al Area
Turismo/Infraestructura marino-costera mal emplazada	Eventos de Erosión Corriente Abajo	• Pérdida de Playa y Propiedades
Intervención de Vegetación Costera y de Dunas	Sedimentación de Areas de Corales y de Lagunas Costeras	• Descenso en las Poblaciones de Especies de Valor Comercial
	Pérdida de Playas	• Pérdida de Propiedades
Industrial/Efluentes inadecuadamente tratados	Contaminación de Estuarios	• Disminución de Poblaciones de Especies de Valor Comercial
Agrícola/Escorrentía de Agroquímicos	Contaminación de Estuarios y Acuíferos	• Disminución de Poblaciones de Especies de Valor Comercial • Pérdida de Fuentes de Abastecimiento de Agua para Consumo Humano
Mal manejo de Cuencas	Aumento en la Turbidez de las Aguas Costeras	• Pérdida de Areas de Corales y de Valor Recreacional, etc.
Transporte/Desarrollo Portuario		
1. Comercial	Relleno de Areas Inundables	•Pérdida de Areas con potencial Salinero o para Acuacultura
2. Petrolero	Contaminaciøn de Aguas Costeras	•Disminuciøn de Poblaciones de Especies de Valor Comercial y del Valor Recreacional del Area

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Nota: Los ejemplos presentados constituyen sólo una muestra de una larga lista de los efectos e impactos ambientales y socioeconómicos negativos que podrían ser generados por diferentes usos y actividades costeras.

Existen, asimismo, problemas de procedimientos y de organización que impiden una gestión adecuada de los espacios y recursos costeros:

1. Bajo nivel de coordinación entre entes de la administración pública.
2. Déficits de información básica, dispersión de la información, o información—aún sin procesar—de poca utilidad para la toma de decisiones.
3. Planes desarrollados a escalas macro—bajo nivel de detalle y poco útiles para los procesos de obtención de permisos y toma de decisiones—o desarrollados para ambitos limitados, ignorando las consecuencias que las propuestas podrían generar sobre otros espacios y recursos.
4. Bajo nivel de concientización con respecto a los ecosistemas costeros, su importancia y las consecuencias de la degradación de ciertos espacios y recursos naturales.
5. Toma de decisiones realizada en función de consideraciones de tipo económico y para el corto plazo.

GESTIÓN DE COSTAS EN VENEZUELA

La competencia institucional, en materia de gestión de costas, le ha sido atribuida a los siguientes organismos: Ministerio de Transporte y Comunicaciones (Capitanía de Puertos), Ministerio del Ambiente y de los Recursos Naturales Renovables, Ministerio de Desarrollo Urbano, CORPOTURISMO, Ministerio de Agricultura y Cría, Ministerio de la Defensa, Ministerio de Energía y Minas y a los Municipios, entre otros entes centralizados y descentralizados de la administración pública.

Venezuela no cuenta con un Programa Formal de Gestión de Costas; sin embargo, posee una estructura legal e institucional que permitiría que la Ordenación Territorrial se conviertiese en el marco de un Programa Integrado de Planificación y Manejo que garantice la conservación y el desarrollo de las áreas y recursos costeros.

Los problemas de organización que impiden una gestión adecuada de las costas, están estrechamente vinculados a:

- Falta de claridad en la definición de metas y objetivos.
- Déficits Presupuestarios a nivel central, regional, y local.
- Metodologías obsoletas para la gestión de costas.
- Predominio del corto sobre el largo plazo.
- Conflictos jurídicos y administrativos.
- Insuficiente divulgación de la información.
- Bajo nivel de formación de personal, para el manejo de costas.
- Limitada participación pública en la toma de decisiones.

OBJETIVOS DE UN PROGRAMA DE MANEJO DE ÁREAS COSTERAS

El objetivo principal de un Programa de Manejo de Áreas Costeras es integrar al desarrollo y a la conservación de estos espacios y recursos, a fin de optimizar los beneficios sociales y económicos que éstos puedan generar para las generaciones presentes y futuras. Los objetivos específicos son:

- Protección de los valores naturales de las costas.
- Maximizar el acceso público a estas áreas, incrementando las oportunidades de recreación y educación.
- Asegurar que se de prioridad, en el proceso de asignación de usos del territorio, a las actividades dependientes de las costas.
- Proteger las áreas de alta productividad biológica y habitats de especies amenazadas o en peligro de extinción, promoviendo a la vez la investigación científica.
- Promover la recuperación de espacios y recursos degradados.
- Asegurar que los desarrollos de magnitud significativa que se proyecten para estas áreas están supeditados a una evaluación de impacto ambiental.
- Garantizar que exista un proceso de consulta pública e institucional para evaluar la conveniencia de proyectos que puedan modificar significativamente las costas.

La participación pública constituye un elemento esencial para la implementación exitosa de los planes de ordenación de las áreas costeras, toda vez que si una porción siginificativa de la población afectada por los planes, no entiende sus objetivos y apoya las acciones propuestas, el plan fracasará. La participación pública puede contribuir en:

- La identificación de los recursos importantes para los habitantes del área.
- La identificación de todas las alternativas de manejo posibles.
- Reacciones frente a valores cuantificables y no cuantificables, y negociaciones entre alternativas.
- El desarrollo de mecanismos de compensación.
- Evitar litigios costosos e innecesarios.
- Trabajar hacia un concenso sobre una alternativa preferida.
- Constituirse en vigilantes o guardianes ambientales e informar acerca de actividades o desarrollos ilegales.

ESTRATEGIAS DE GESTIÓN DE ÁREAS COSTERAS

Las principales estrategias empleadas en la gestión de costas, integran a dos o más de las siguientes, según Sorensen y Brandani:

- Planes Nacionales.
- Planes Sectoriales.
- Establecimiento de Areas Naturales Protegidas.
- Evaluación de Impacto Ambiental (EIA).
- Restricciones para la ocupación o uso de la porción terrestre de los espacios costeros.
- Planes de Ordenación Territorial.
- Planes Especiales Para Areas Costeras Críticas.
- Bancos de Datos y Atlas Costeros.

En Venezuela se emplean todas las estrategias señaladas, aun cuando su aplicación persiga objetivos distintos a la gestión integrada de los espacios y recursos costeros. El Ministerio del Ambiente y de los Recursos Naturales Renovables es el ente responsable o co-responsable de la formulación e implementación de la mayoría de los instrumentos de gestión señalados. Esto convierte al MARNR en la institución ideal para iniciar un Programa formal de Gestión Integrada de Costas.

PROYECTO: ORDENACIÓN Y MANEJO DE ÁREAS COSTERAS (CONVENIO: MARNR-PNUMA)

Las actividades desarrolladas en el marco del Convenio MARNR-PNUMA, Proyecto: Ordenación y Manejo de Areas Marinas y Costeras, han sido orientadas hacia la generación de planes pilotos de ordenación de áreas costeras críticas. En la realización de los mismos se concluye que, utilizando como marco a la ordenación del territorio y con ajustes y mejoras en los procesos tradicionales de toma de decisiones, especialmente, enlo referente a la coordinación institucional y a la participación pública en el proceso de planificación y de gestión, se pueden generar instrumentos de manejo que permitan alcanzar los objetivos de conservación y desarrollo de las áreas costeras.

El objetivo del segundo año de actividades del Proyecto es generar un Plan de Desarrollo Integral para una micro-cuenca costera, que se encuentre bajo la jurisdicción de sólo un Municipio. En este proceso se involucrará, desde el principio, al Gobierno local y a las comunidades costeras, con el objeto de sentar las bases para alcanzar concensos que garanticen la viabilidad de la implementación del Plan, el cual esperamossea aprobado en Concejo y publicado en Gaceta Municipal.

La metodología para la selección del Municipio donde sea mas factible la implementación de un Plan de estas características y las experiencias derivadas del proceso de planificación servirán de modelo a otros municipios del país, asi como a otros países costeros de la Región del Caribe.

INTERGOVERNMENTAL STUDIES

INTERGOVERNMENTAL OCEANOGRAPHIC COMMISSION

ACTIVITIES AND PLANS OF THE IOC RELATED TO COASTAL ZONE MANAGEMENT AND SEA LEVEL RISE

George A. Maul, Vice Chairman
Subcommission for the Caribbean and Adjacent Regions
Intergovernmental Oceanographic Commission of UNESCO
Miami, Florida

The Intergovernmental Oceanic Commission (IOC) is an autonomous body of UNESCO. It is charged with oceanographic activities on a par with the meteorological activities of the World Meteorological Organization (WMO) and the environmental activities of the United Nations Environment Programme (UNEP). Headquartered in Paris, the IOC supports programs on various aspects of ocean research, monitoring, and development, including information exchange and coordination; climate change and the ocean; ocean sciences; marine pollution research and monitoring; ocean services; training, education, and mutual assistance; and operation of subsidiary bodies and regional organizations. Since oceanic effects on human life know no artificial boundaries or disciplines, the IOC actively cooperates with many UN bodies, such as WMO, UNEP, Food and Agriculture Organization (FAO), International Meteorological Organization (IMO), etc., and with scientific and technical committees, such as the ICSU, CCCO, SCOR, and their numerous programs including TOGA, WOCE, GEWEX, JGOFS, GLOBEC, and the WCRP.

Specific scientific and technical activities are carried out by IOC Groups of Experts. For sea level, the IOC Group of Experts as part of GLOSS, or the Global Sea Level Observing System, started in the 1980's. GLOSS is commissioned to establish, maintain, improve, and expand our knowledge of coastal sea level change on a global scale, but with regional working groups to attack local problems. The GLOSS plan is to have about 300 tidal gauges permanently operating and reporting monthly and annual means to the IOC cosponsored Permanent Service for Mean Sea Level (PSMSL) in the United Kingdom. Site selection for the 300 global tidal gauges is based on scientific and technical needs, and is coordinated through the GLOSS at biannual meetings.

On a regional scale, using the area encompassed by the Gulf of Mexico/Caribbean Sea/Bahamas/Northeast South America as an example (an IOC subcommission known as IOCARIBE), the GLOSS network has 25 tidal gauges operating, with plans for doubling this coverage by the turn of the century. Within IOCARIBE, a joint IOC/UNEP Task Team is studying the effects of climate change-induced sea level rise on coastal ecosystems, including deltas, estuaries, wetlands, coastal plains, coral reefs, lagoons, mangroves, sea grass beds, fisheries, rivers, coastal lakes, and beaches; also included are studies of climate impacts on socioeconomic, infrastructure, and anthropologic activities. These studies are coordinated with other IOC programs in the region including ocean sciences in relation to nonliving resources; ocean science in relation to living resources; global investigation of pollution in the marine environment; the international ocean data exchange; the integrated global ocean services system; and other activities, including (training, education, and mutual assistance) and of course GLOSS.

OBJECTIVES OF THE GLOBAL OCEAN OBSERVING SYSTEM (GOOS)

Long-term, systematic measurements of the ocean are a key element in understanding and predicting environmental change and in providing the information necessary for environmental protection. The IOC has supported the initial development of the necessary observational elements, and in 1991 confirmed the high priority of establishing a Global Ocean Observing System (GOOS) to address physical, chemical, and biological aspects of the ocean. WMO and UNEP have agreed to cooperate in the development, implementation, and maintenance of GOOS, particularly those aspects of GOOS that are related to the Global Climate Observing System and to global coastal monitoring.

The GOOS is intended to meet the needs for: (1) monitoring, assessment, and subsequent prediction of environmental and climate changes globally, regionally, and nationally; (2) data and data products required by nations for efficient and rational use of ocean resources, protection of marine environment, and coastal zone management, as well as for other practical applications; and (3) research toward improved understanding, modelling, and prediction of the state of ocean systems and the role of the ocean in the climate and environmental change.

A primary initial objective of GOOS is to ensure commitment to long-term measurements of the ocean. This includes observations of major physical, chemical, and biological properties of the global ocean, the coastal zone, and enclosed and semi-enclosed seas. Mechanisms and infrastructures required for operational exchange and dissemination of data, information, and products are part of GOOS.

GOOS will be established by member states through concerted and coordinated actions, and implemented through nationally owned and operated facilities and services. Coordination will be provided by IOC, in cooperation with WMO and UNEP. The data acquired by GOOS must be exchanged fully and freely on a timely basis for the benefit of all. GOOS will require that national and regional oceanographic services be established to enable countries to fully and efficiently apply the data and information resulting from GOOS.

STRUCTURE OF THE GOOS

GOOS will provide information for a variety of objectives and users. For convenience, the GOOS structure has been divided into different sets of aims and products to be achieved and produced. These sets constitute GOOS modules. Each module is aimed at fulfilling the data and product requirements of a reasonably well-defined user community. Some products may be unique to the relevant customer community, some may overlap needs of different customers, and some may be generic to all.

There are five planned GOOS modules: (1) climate monitoring, assessment, and prediction; (2) monitoring and assessment of marine living resources; (3) coastal zone management and development; (4) assessment and prediction of the health of the ocean; and (5) marine meteorological and oceanographic services. It is expected that there will be close interaction among the different modules, both nationally and internationally, to maximize effectiveness.

MAJOR ELEMENTS OF THE GOOS

GOOS will consist of the following major elements:

- *Measurement System.* Initially to be built upon existing systems, such as the integrated global ocean services system (IGOSS), GLOSS, and World Weather Watch (WWW), GOOS will nevertheless require the development and application of new technology to ensure global long-term coverage of essential parameters. This new technology will include developments with regard to satellite instrumentation, autonomous vehicles and moorings, acoustic and other averaging techniques, automated shipboard observations, and telemetry systems.

- *Data and Information Management.* Existing data management systems within IGOSS, international ocean data exchange (IODE), WWW, etc., need to be considerably improved to ensure timely delivery of high-quality data in operational mode required for ocean and climate modelling and to provide users with easy access to GOOS data bases. GOOS will require the continuing commitment of participating countries to the establishment, maintenance, validation, description, accessibility and timely distribution of high quality, long-term data sets.

- *Data Analysis, Preparation, and Dissemination of Data Products.* GOOS, when fully operational, will provide ocean data sets that will allow the production of regular global and regional oceanographic analyses and predictions. The GOOS plan suggests designating ocean data and information product centers, both global and regional, that will require international cooperation and support.

- *Modelling.* The success of GOOS is dependent on the development of physically realistic numerical models of the ocean. The data from GOOS will initially provide the information needed to develop and improve the models; operational prediction models will be initialized and regularly updated by incorporation of data from GOOS. The plan provides for close interaction between the observational program and model development. Participating countries will be invited to establish national modelling groups, and the establishment of an international global ocean analysis and modelling center through cooperative efforts of member states is recommended.

- *Technical Assistance, Training, and Technology Transfer.* To facilitate broad international participation vital to its success, GOOS must include an international long-term training and assistance program, together with transfer of relevant technology, to support users and involve developing countries in observational and data analysis activities. In addition, the establishment of national and regional oceanographic services and centers must be promoted.

Both IOC and WMO emphasize that GOOS must be built as far as possible on existing ocean observing and data management systems, such as IGOSS, WWW, GLOSS, DBCP, IODE and MARPOLMON, as well as progressive implementation of new elements and capabilities. The design, planning, development, and effective implementation of a scientifically sound and cost-effective GOOS requires close permanent interaction with ongoing and planned international research programs that are addressing issues of global environment and climate changes.

MAJOR PROVISIONS OF THE GOOS PLAN

The GOOS plan includes major provisions and actions, on both national and international levels, required for successful planning and implementation. Particular attention is given to actions to be taken during 1992-95, divided into three categories:

- *International Actions.* Support for approval of a GOOS declaration by UNCED; endorsement of the draft plan; formulation of a strategy for GOOS development by relevant international bodies; establishment of an international mechanism for coordinated GOOS planning; preparation of an international agreement for GOOS; identification of requirements for support and assistance; promotion of collaboration in the application of satellite remote sensing; preparation of a GOOS status report; and public information and education.

- *International Actions for GOOS Modules.* Design of the GOOS climate module (by OOSDP in cooperation with JSTC/GCOS; preparation of an international continuous plankton recorder survey program (by CCCO/GLOBEC group); implementation of specific pilot projects proposed in the GOOS module on coastal zone management and development (by joint efforts of UNEP and IOC regional groups); and strengthened and expanded activities of IOCWMO/IGOSS, IODE and GLOSS in developing the GOOS module concerning marine meteorological and oceanographic services.

- *Action by Member States.* Establishment of national GOOS offices or GOOS contacts to serve as focal points for national GOOS participation and to foster the necessary support among all relevant national agencies; identification of possible participation in and support for GOOS planning and development; increased support for existing ocean observing and data management systems (IGOSS, GLOSS, DBCP, IODE) through increased and timely submission of oceanographic data and data products for international exchange; increased support for the development and deployment of new technology to meet the requirements for an operational GOOS; and identification of possible support for activities related to training, education, and mutual assistance, particularly in relation to training of specialists in data acquisition, interpretation and analysis, and provision of instruments and equipment identified within the framework of IGOSS, GLOSS, and IODE activities.

COORDINATION OF THE GOOS

The IOC is providing the coordination and leadership necessary to establish the Global Ocean Observing System in cooperation with WMO, UNEP and ICSU. At the same time, it is looking to its member states to make the necessary commitments to ensure the reality of the system. Together the IOC, associated international organizations, and member states can lead the way in environmental monitoring, prediction, and protection.

GLOBAL CLIMATE CHANGE AND COASTAL LAND LOSS: MANAGEMENT AND DECISION MAKING IN SUPPORT OF SUSTAINABLE DEVELOPMENT WITHIN THE CARIBBEAN AND ADJACENT REGIONS

Georges Vernette
Intergovernmental Oceanographic Commission
Subcommission for the Caribbean and Adjacent Regions
Cartagena, Colómbia

ABSTRACT

Shoreline instability is widespread in the Caribbean area. Causes are both natural and man-made, and have serious implications for countries of the region that rely extensively, and in some cases almost exclusively, on low-lying coastal margins and their resources for settlement, transportation, recreation, and economic development. A major cause for concern is the possibility of increased land loss due to future global climate change and sea level rise, especially for the many Caribbean states with populations below or close to present sea level.

While awareness of the need for improved coastal resource management is increasing, most program initiatives address areas of living resources. Skills to deal with the complex area of coastal erosion are not uniformly developed, and decision-making and management capacity lag far behind scientific institutional capability in many locations.

To address these critical issues, IOCARIBE has developed a program with thrusts in three major areas: (1) region-wide training using structured, sequential courses dealing with measurement and modeling of shoreline change, forward modeling, resource-use planning, decision making, and program development, and integrated coastal zone management; (2) regional and local case studies of coastal reaches that are of special concern with respect to erosion, using an action/decision management-driven approach; and (3) publication and dissemination of training manuals, case study results, and guidebooks for coastal area landowners, developers, and legislators, on approaches for improving management of this zone in light of existing and projected future problems. By providing significant opportunities for cooperation and information exchange, IOCARIBE with its member states expects to build a system of mutual support and technical/managerial exchange in matters relating to Caribbean coastal zone management. The cumulative experience gained will provide a platform for the Caribbean to respond to problems of regional and global environmental change in this dynamic zone.

Two important features of the program are: (1) skills for training and for conducting case studies exist within the institutional capacity of respondents who have committed themselves to this program, and (2) using the traditional IOCARIBE approach, substantial savings will be made by additional commitment of these institutions to provision of counterpart professional time, facilities, and logistical support. For this 5-year program, IOCARIBE seeks a total of $US 2.13

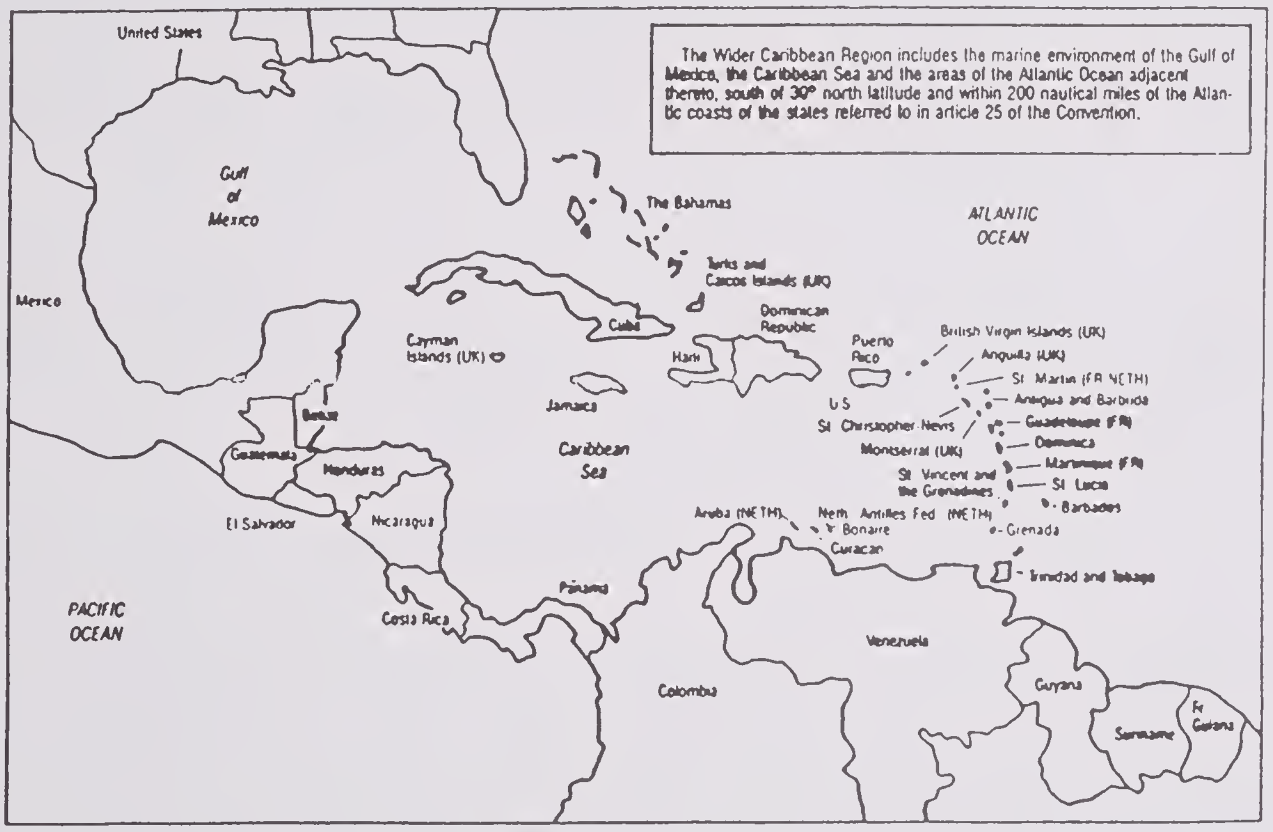
million, of which $US 0.63 million (or 30 percent) represents counterpart funds from participating institutions. External support required, therefore, totals $US 1.5 million.

INTRODUCTION

GEOGRAPHICAL LOCATION

This program proposal is submitted by the Intergovernmental Oceanographic Commission, Sub-Commission for the Caribbean and Adjacent Regions (IOCARIBE). IOCARIBE is a legally constituted body within the Intergovernmental Oceanographic Commission (IOC) of UNESCO, with a Secretariat in Cartagena, Colómbia. The areas of IOCARIBE responsibility correspond to the definition of areas in the Wider Caribbean region of the United Nations Environment Programme (UNEP, see Figure 1). The work plan covers the coastline and continental shelf, as described in the criteria of the IOC Group of Experts for Ocean Science in Relation to Non-Living Resources (OSNLR).

FIGURE 1. TERRITORIES OF THE CARIBBEAN AND ADJACENT REGIONS



The Wider Caribbean Region includes the marine environment of the Gulf of Mexico, the Caribbean Sea and the areas of the Atlantic Ocean adjacent thereto, south of 30° north latitude and within 200 nautical miles of the Atlantic coasts of the states referred to in article 25 of the Convention.

The territories covered by this area are the same as for the Wider Caribbean region, as described by the United Nations Environment Programme (UNEP, 1989a).

PREVIOUS PROJECT ACTIVITIES

This proposal was developed as a core component of the IOCARIBE program focus within the IOC framework of OSNLR. At the Second Session of the IOCARIBE Sub-Commission in Havana, December 1986, several recommendations were made that led to program development. These recommendations included consideration of beach dynamics as a priority area; identification of pilot areas to implement continuous monitoring activities; and development of courses and atlases on coastal oceanography. The proposal for courses was followed by holding a three-week training course on coastal oceanography for participants from 11 Caribbean countries during May–June 1988, in Cartagena (CIOH/IGBA, 1988), with emphasis on coastal physical and geological processes.

The IOC guiding Group of Experts for OSNLR at its Third Session in Bordeaux, France, February 1989, stressed its support for projects in coastal areas, including the Caribbean. This was followed by an Interdisciplinary Seminar on Research Problems in the IOCARIBE region held in conjunction with the Third Session of the IOCARIBE Sub-Commission in Caracas, Venezuela, November–December 1989, where a preliminary program proposal entitled "Impact of Sea-Level Variations on Coastal Zones: Effects on Erosion and Sedimentation" was compiled.

IOCARIBE convened an Ad Hoc Regional Expert Group for OSNLR during the Second Congress on Maine Sciences in Havana, Cuba, June 1990, to further discuss this proposal. At that time, there was a fundamental shift in approach to the program from scientific measurement and modeling to management and decision making based on information relating to coastal change problems. The revised document was submitted to the International Center for Ocean Development (ICOD), Canada, which agreed to provide financial support for more detailed elaboration of the program work plan, institutional inputs, objectives, methodology, and budget. This proposal is the direct result of the ICOD-supported program development. The proposal incorporates detailed responses (Table A-1) from regional institutions to a memorandum circulated from IOCARIBE requesting details of potential involvement in training, research, and case studies. Preliminary approaches were made to potential funding agencies using a Project Concept Statement, and the approach to programming and funding takes account of the response from these organizations, particularly with respect to agency policy on support areas for funding activities.

BACKGROUND AND JUSTIFICATION

COASTAL LAND USE AND LAND LOSS PROBLEMS IN THE IOCARIBE REGION

The majority of countries within the Wider Caribbean region (Figure 1) are small—less than 1,000 sq. km.—and there depend heavily on coastal areas and their resources. In all island states, and in several continental countries, the majority of the population lives within 5 kilometers of the coastline, in areas close to or below present sea level (Nurse, 1989, 1990; Hendry and Nurse, in press). Associated with this settlement pattern are industrial, housing, infrastructural, and communication networks (roads, seaports and airports, telecommunications etc.), plus traditional fishery and agricultural activities, all of which represent enormous capital investments. These areas also contain much of the cultural and historical heritage of each country.

Reliance on coastal area resources has increased significantly over the last three decades with a boom in the regional tourism industry, which has now become a major—and in some instances the most important—single source of income and foreign exchange (Table 1). Related resources, including beaches, reefs, wetlands, and coastal waters, are part of the overall environmental attraction for visitors and form part of a mutually interdependent natural support system in the coastal area.

TABLE 1. ECONOMIC INDICATORS OF THE VALUE OF COASTAL RESOURCES TO SELECTED CARIBBEAN COUNTRIES

Country	Area Km^2	GDP (US$M)	Visitor Spending	
			(US$M)	(GDP %)
Anguilla	91	42	24	57
Antigua/Barbuda	440	381	232	61
Bahamas	13,942	2,512	1,230	49
Barbados	431	1,707	505	30
Belize	22,960	305	79	26
British Virgin Islands	150	152	125	82
Cayman Islands	260	580	180	31
Cuba	114,525	29,415*	223*	0.8
Dominica	750	152	19	13
Dominican Republic	49,520	5,037*	616	12
Grenada	345	182	53	29
Guadeloupe	1,373	1,100*	220*	20
Guyana	215,000	254	30	12
Haiti	27,750	1,900*	75	4
Jamaica	11,424	3,884	593	15
Martinique	1,080	1,200*	230*	19
Montserrat	102	56	11	20
St. Kitts/Nevis	269	107	60	56
St. Lucia	616	223	145	65
St. Vincent/Gren.	388	168	43	26
Surinam	163,820	900*	16*	2
Trinidad and Tobago	5,128	4,339	81	2
Turks and Caicos	417	69	34	49

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*1988 data; all other data are for 1989.

Sources: McElroy and de Albuquerque (1989) and CDB, Regional Statistics (1990).

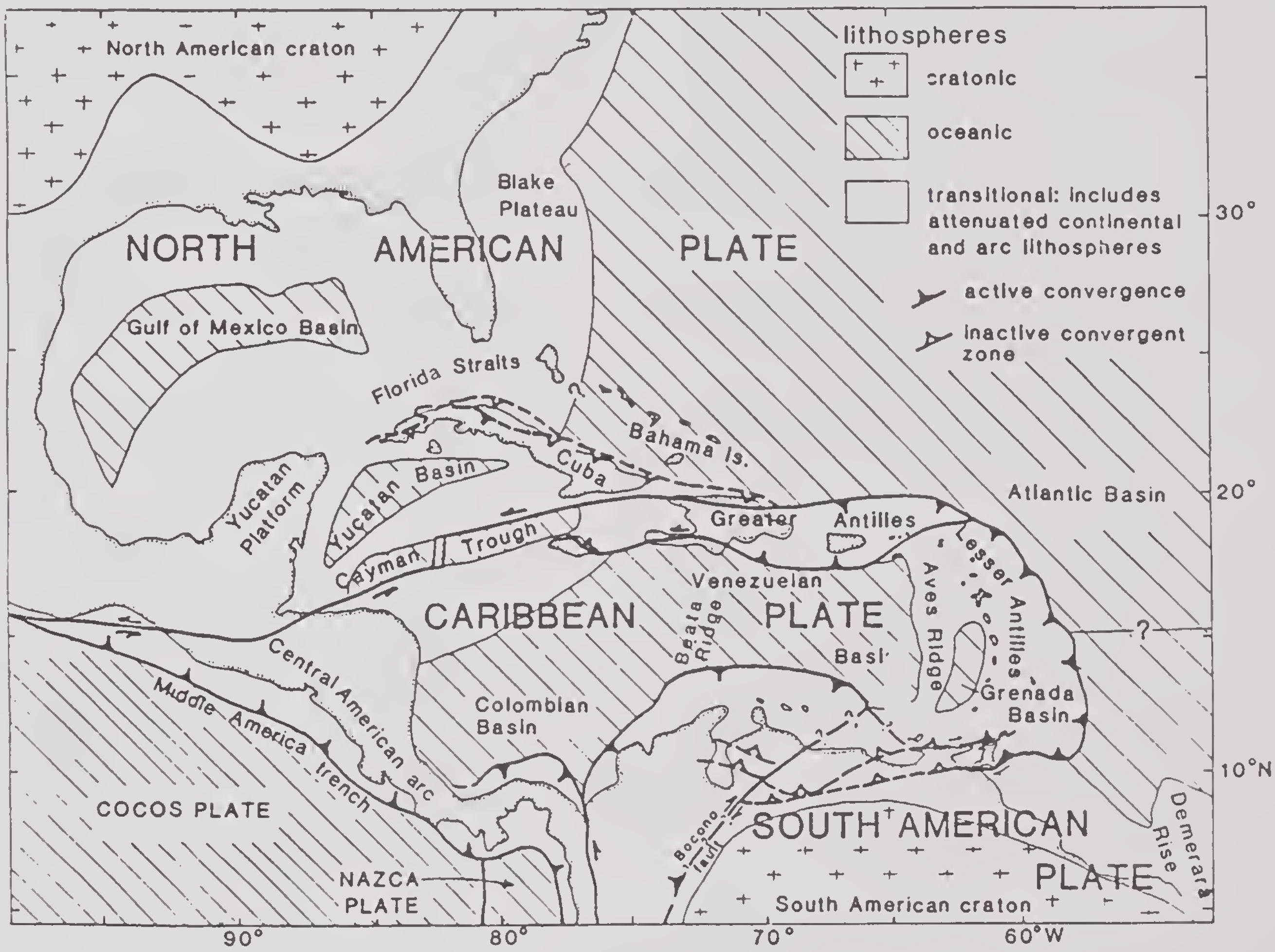
This pressure for space in area-restricted coastal locations and the pace of development have placed enormous stress on coastal ecosystems and have led directly to resource-use conflicts, habitat and environmental degradation, shoreline erosion, and loss of ecosystem function and value (UNEP, 1989a). Due to inadequate site planning and setbacks, inappropriate coastal construction, poor sand management, damage to protective reefs and sea grass systems, and the recent destructive effects of major hurricanes, such as Allen, David, Gilbert, and Hugo, coastal land loss has now become a critical problem and is threatening a large portion of the economic base of the region (Thieler et al., 1989; Hall et al., 1990; Hendry and Bacon, 1990; Hendry, in press, a; Hendry and Nurse, in press).

The capability of Caribbean nations to come to grips with problems of coastal land loss is in most instances substantially below the level necessary to define appropriate and timely interventions. In only a few countries are systematic programs for coastal monitoring and measurement under way, and in several instances these programs have only begun in the last few years (Cambers, 1990; Hendry, in press, b). Responses to land loss problems are in most cases ad hoc and take little account of potential negative impacts on adjacent coastlines, or downstream ecological or process-response feedback to the chosen intervention (Hendry and Nurse, in press; Imbert, in press).

OVERVIEW OF COASTAL CHANGES IN THE CARIBBEAN AND ADJACENT REGIONS

A detailed review of coastal erosion in the Caribbean and adjacent areas (Figure 1) indicates that shorelines are in general retreating through historical times (Hendry, inn press). This continues a trend that developed during the earliest periods of shelf submergence (c. 8,000–10,000 years before present) when sea level was rising after the last global glacial maximum event, which took place about 18,000 years ago. The nature of shoreline change over historical and earlier periods, however, has varied considerably throughout the region. The reasons for this variability reflect regional differences in geological structure, sediment supply, and coastal processes (see Figure 2). Broadly, coastal types and the sedimentary processes that dominate them can be grouped as follows:

FIGURE 2. GEOLOGICAL CONFIGURATION OF THE CARIBBEAN AND ADJACENT REGIONS



Complex tectonics give rise to regional variability in coastal history and create significant differences in the sediment budgets of coastal areas.

1. *Northern South America:* Coastal sedimentation is dominated by massive inputs of material derived from the continental interior, transported to the shield by major river systems, such as the Amazon (Brazil), Orinoco (Venezuela), and Magdalena (Colómbia). The sand shoals, deltas, and mudbanks generated by river input and longshore transport are continually moving, causing repeated phases of accretion and erosion. On the coastline of the Guyanas, cyclical shoreline advance and retreat accompany passage of huge mudbanks northwestward along the continental shelf. Major population centers occupy land at or below sea level from French Guyana to Colómbia, on extensive, low-lying coastal plains.

2. *Central America:* The coastline of Belize, for example, is flanked by the second-largest barrier reef in the world. In the shelter behind the reef are myriad keys and sand shoals on a shallow platform. In contrast to northern South America, sediment transport is limited, but the mangrove systems that dominate the coastline are very sensitive to sea level variations. The low-lying coastal plain and its numerous inhabitants are continually exposed to the impacts of sea level variations on several scales, including storm surge. Kjerve and Dinnel (1983) report data that indicate the Belize coastline has been subjected to tropical storm or hurricane effects on average 112 times in every 100 years.

3. *Gulf of Mexico:* Dominated in the north by Mississippi River sediments, shorelines are characterized by barrier island-lagoon-wetland systems, which have retreated during the last few thousand years, except in one or two locations, such as the Ten Thousand Islands area of southwest Florida. There, a relatively sheltered location and slowdown in the rate of sea-level rise in the last 2,000–3,000 years have allowed mangrove communities to expand seaward. Gulf Coast barrier islands are preferred sites for residential development, continually requiring initiation of response strategies to prevent or restrict land loss due to sand movement.

4. *Greater and Lesser Antilles*: Coastlines in this island chain are typified by small, compartmented beaches with restricted sediment supply systems. Shorelines are generally close to the edge of the island shelf, over which much sediment is lost to deeper water, especially during storms. Many of these sediment-starved beaches are backed by old cliff lines, with short distances between the beach face and upland area. These beaches are critical sites: the present trend to erosion, exacerbated by poor planning, inadequate sand management, and other anthropologic impacts described above, may remove even these vestiges of beach from economically essential locations.

5. *Low-Lying (Platform) Islands—e.g., Bahamas, Turks and Caicos, Cayman Islands, San Andres:* This group of islands is characterized by low elevations of nearly all the land area, with the corresponding threat of submergence and major loss of habitable land area due to even small changes in sea level. While the extensive bank areas of the Bahamas and Turks and Caicos produce large volumes of carbonate sediment—the basis for island formation over geological time scales—their exposure to oceanic processes and elevations relative to sea level makes them extremely susceptible to changes in shoreline configuration.

FUTURE IMPACTS OF CHANGES IN SEA LEVEL

Added to concerns over the integrity of coastlines under existing sources of stress are potential impacts due to possible future seal-level rise. Two primary sources of information on projected impacts of future sea level rise for the Caribbean are available. One is the work of the UNEP/IOC Caribbean Task Team on Implications of Climatic Changes in the Wider Caribbean Region (UNEP, 1988; UNEP, 1989b), with recent updates on coastal area impacts by Hendry (in press) and Snedaker (in press). The other is work by the Intergovernmental Panel on Climate Change (IPCC, 1990; WMO/UNEP, 1990). All reports prepared to date indicate that for the Caribbean region, with its population and development focus in low-lying coastal areas, the need to model and plan for the potential consequences of such a rise is extremely important. Indeed, there are few countries covered by the IOCARIBE mandate that would not be significantly affected by sea level changes.

The IPCC has calculated first-order costs for protection of Caribbean shorelines from future sea level rise, including low coasts, cities, harbors, island elevation, and beach nourishment (Table 2). Estimates exclude costs for unprotected dry lands, or ecosystems that may be lost, and impacts of saltwater intrusion and increased storm frequency. With respect to Caribbean island territories, the projected cost of new construction alone is $11.1 billion, at an average of 0.20 percent GDP, the latter figure only exceeded by the small islands of the Pacific and Indian Oceans in a global analysis (WMO/UNEP, 1990).

TABLE 2. COST OF COASTAL PROTECTION BY COUNTRY FOR THE CARIBBEAN AND ADJACENT REGIONS

Country	Total Costs (US $ millions)	Total Costs per capita (US $)	Annual Costs as % of GDP
Anguilla	83	11,786	10.31
Antigua/Barbuda	152	1,870	1.01
Aruba	646	9,447	1.85
Bahamas	2,565	10,915	2.67
Barbados	297	1,172	0.27
Belize	527	3,085	2.93
British Virgin Islands	93	7,725	1.24
Cayman Islands	228	10,350	1.04
Colombia	784	30	0.02
Costa Rica	232	92	0.08
Cuba	2,030	199	0.13
Dominica	14	161	0.17
Dominican Republic	238	37	0.04
El Salvador	27	5	0.01
French Guiana	533	6,197	2.96
Grenada	54	554	0.67
Guadeloupe	236	708	0.20
Guatemala	1,007	123	0.07
Guyana	995	1,250	2.12
Haiti	124	23	0.07
Honduras	32	8	0.01
Jamaica	462	197	0.19
Martinique	192	585	0.14
Mexico	9,889	123	0.06
Montserrat	3	225	0.09
Neth. Antilles	908	5,159	0.66
Nicaragua	956	282	0.35
Panama	263	118	0.06
Puerto Rico	334	102	0.02
St. Kitts/Nevis	140	3,033	2.33
St. Lucia	123	879	0.82
St. Vincent & Gr.	55	497	0.55
Surinam	2,622	6,638	1.94
Trinidad & Tobago	1,720	1,431	0.21
Turks & Caicos	223	24,739	8.10
USA*	86,819	360	0.02
Venezuela	3,155	177	0.05
U.S. Virgin Islands	230	2,108	0.26

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* This figure includes all coasts, not just those bordering the Wider Caribbean region.

Source: IPCC Coastal Zone Management Subgroup to the (IPCC, 1990), summary of which appears in WMO/UNEP (1990).

Options for dealing with future sea level change will fall in three main areas: (1) retreat, (2) accommodation, or (3) protection (known as RAP). Options chosen will clearly depend upon decisions made at the country level, but the decision-making process that must accompany this activity has to be well informed. The IOCARIBE program has a major role to play in training and providing decision-making tools to the very persons who over the next few years will be called upon by governments to provide this essential advice.

THE IOCARIBE PROPOSAL

A PROGRAM TO SUPPORT SUSTAINABLE DEVELOPMENT OF CARIBBEAN COASTAL AREAS

In the light of (1) present reliance on coastal areas for economic development activity, (2) existing conditions of stress due to environmental impacts and land loss, and (3) projected increases in coastal development and of sea level due to global climate change, it is critical that Caribbean nations develop the tools for making appropriate management decisions in relation to present and projected future change in coastal land areas.

There is substantial disparity in capability among the countries of the Caribbean with respect to decision making and implementation for coastal land-loss problems, and everywhere, undeveloped capacity for understanding and acting upon the potential impacts of climate change. Even in countries with significant technical capability there is a large gap between the ability to obtain basic scientific information on coastal change and actions by decision makers who must allocate resources to deal with perceived or measured problems. This statement is supported by the response on a regional basis to the questionnaire from IOCARIBE (Appendix 8.2), where many institutions saw this program as an opportunity to expand existing scientific data collection, despite the fact that IOCARIBE expressly pointed out the need for linkages between data acquisition and decision-making. It is further supported by consideration of regional and local programs in coastal area management (Appendix B), where there are many projects dealing with, for example, marine pollution, water quality, marine parks and coastal productivity, but few that incorporate the key area of coastal land loss and its implications.

Through this program, IOCARIBE with its unique, well-established links to both the technical community and the political directorate region-wide is ideally placed to develop a training and applications process, aided by local, detailed case studies of coastal change problems, that will support efforts taking place with respect to living resources to provide sustainable management strategies for coastal areas in the Caribbean and adjacent regions.

GOAL

IOCARIBE, in cooperation with regional research institutions, coastal management agencies, and governments, seeks to develop essential skill in decision making for appropriate intervention in coastal stability problems. Through structured, sequential training programs, site-specific case studies, workshops, and publications, IOCARIBE will provide for the development of a management framework that is manager/decision/action driven. This framework will generate evaluation of emerging shoreline problems, options for responses based on beat available technical information, decisions given existing constraints, and actions or planned actions and evaluations. The development of this management framework will be conducted so as to allow for decision making at the local (territorial) level and will provide for collective inputs to management decisions based on the cumulative experience of the participant institutions.

OBJECTIVES

LONG-TERM

- Create an improved distribution of skills and capability throughout the IOCARIBE regions for decision making and management in response to present and emerging problems of coastal land loss due to erosion and sea level rise.

- Provide for a system of mutual support and technical/managerial exchange among countries of the IOCARIBE region in matters relating to management of nonliving marine resources.

- Improve regional capability to respond to issues and problems emerging from future global climate change.

SHORT-TERM

- Develop and deliver a structured sequence of training modules in Spanish- and English-speaking territories, building from basic techniques of data acquisition on shoreline changes, through monitoring and measurement, forward modeling, decision making, and project development to resource-use planning and integrated coastal zone management.

- In collaboration with regional coastal management authorities, initiate a series of local case studies addressing serious erosion situations, or sites of potential land loss due to future sea level change, incorporating natural science and socioeconomic considerations in decisions about optimal responses to these problems.

- Generate an ongoing and residual information base for professionals and lay persons through preparation and publication of training manuals for program courses; results of case studies, and guidebooks for coastal zone planners, landowners, and developers, on how to blend development requirements with the realities of living in this dynamic zone.

RELATIONSHIP WITH OTHER REGIONAL AND GLOBAL PROGRAMS

In developing this proposal, IOCARIBE is conscious of the wide range of programs currently being undertaken on environment and resource management within and outside the Caribbean region. Special care is being taken to ensure that duplication and overlap with the work programs of various other projects do not occur, and where there is commonality, that exchange of information and ideas takes place. Because the complex issue of management in relation to shoreline changes is as yet poorly understood, and because many programs have a focus on living resource management (Appendix A), this program is complementary to other efforts.

The emphasis is on application of technical information in the management process, and not on primary data collection, except where insufficient information exists. This program will, therefore, make maximal use of data bases developed elsewhere, to which program participants have ready access, either through direct involvement in other programs or association with research institutions and libraries. The Program Coordinator, working through the IOCARIBE Secretariat, will ensure close collaboration with other IOCARIBE programs, such as (1) "Marine

Pollution and Control Program for the Wider Caribbean" (CEPPOL), (2) "Recruitment on Coastal Demersal Communities" (TRODERP), and IOC activities on ocean services, especially the important "Global Sea Level Observing System" (GLOSS), the "Integrated Global Ocean Services System" (IGOSS), the "International Oceanographic Data and Information Exchange System" (IODE), and the "Aquatic Sciences and Fisheries Information System" (ASFIS).

Lines of communication have already been opened prior to program submission with three new regional programs on resource management. These are CARICOMP, ENCORE, and CFRAMP (Appendix A). Ongoing dialogue is enjoyed between IOCARIBE and UNEP on their joint regional Task Team on Implications of Climatic Changes in the Wider Caribbean Region.

This program also recognizes regional activities under the aegis of the International Geological Correlation Program, Project 274 "Coastal Evolution in the Quaternary," and actives of the Organization of American States, UNDRO, and CARICOM in hazard research, especially as this relates to coastal areas, and will seek to exchange information and technical data as appropriate.

APPROACH AND METHODOLOGY

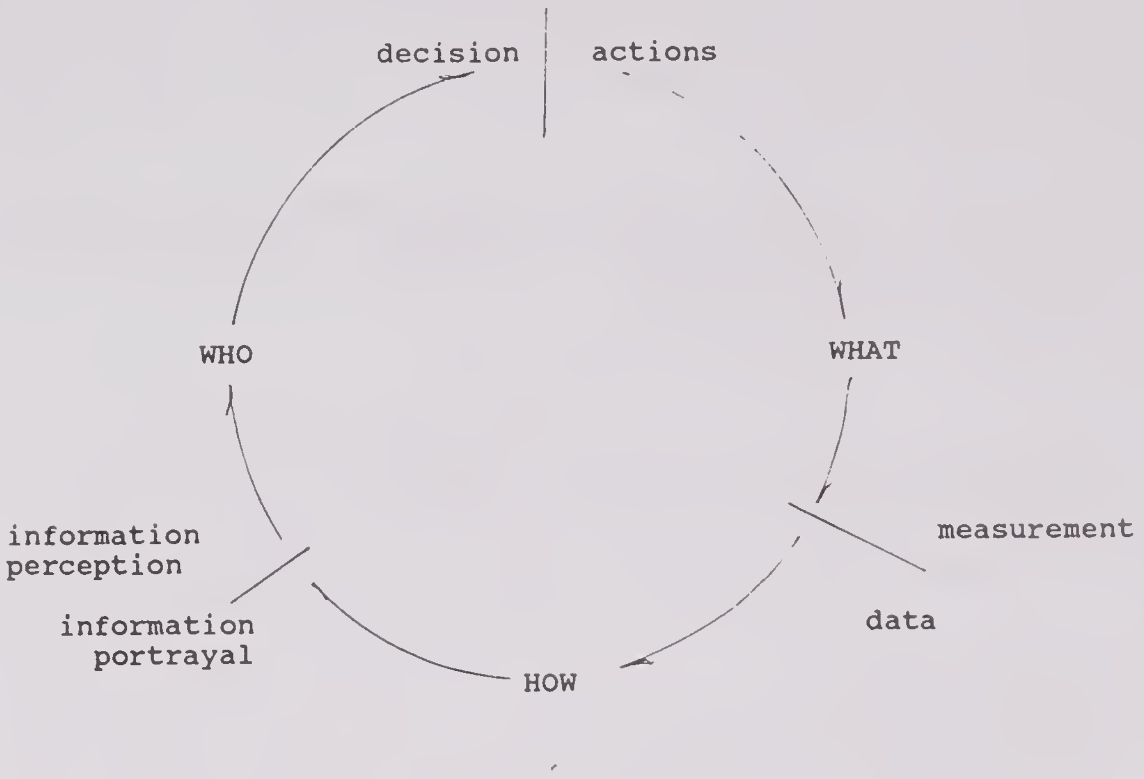
This cooperative program has technical, operational, and overview aspects for achieving the above goal of managing coastal changes in the Caribbean region. The technical aspect relates to techniques for identifying and understanding coastal change mechanisms. The operational aspect is concerned with actual case studies and decisions on optimal response options. The overview or regional aspect involves the regional capability technically and managerially. The methodologies for these levels and the relationship between them are described below.

For this program, a key building block is the management circle of Figure 3 (adapted from Kurstedt, 1987). The features of this approach are:

- Identification of what is to be managed, with which tools, and by whom.
- Specification of the elements of management: measurements -> data -> information -> decision -> action.
- The need for balance or matching across the interfaces—for example, measurements, data, and information relevant to possible actions, and information portrayal appropriate to decision makers' perceptions.

For this coastal changes program, we envision three management levels or circles (Figure 4). Circle I is at the technical level—designed to manage the dissemination of techniques and information required for a case study, both natural scientific and socioeconomic. Circle II is the operational level and is devoted to managing actual case studies—e.g., in a particular country. Thus, Circle II is supported by Circle I and interacts in turn with Circle III, the level of regional information, strategies, and capabilities. The three circles are described in Tables 3, 4, and 5. The training course outlines that follow provide more details on the methodologies mentioned in these tables.

FIGURE 3. SCHEMATIC OF BALANCED MANAGEMENT CIRCLE



Source: Kurstedt, 1987.

FIGURE 4. SCHEMATIC OF LEVELS OF PROJECT ACTIVITY

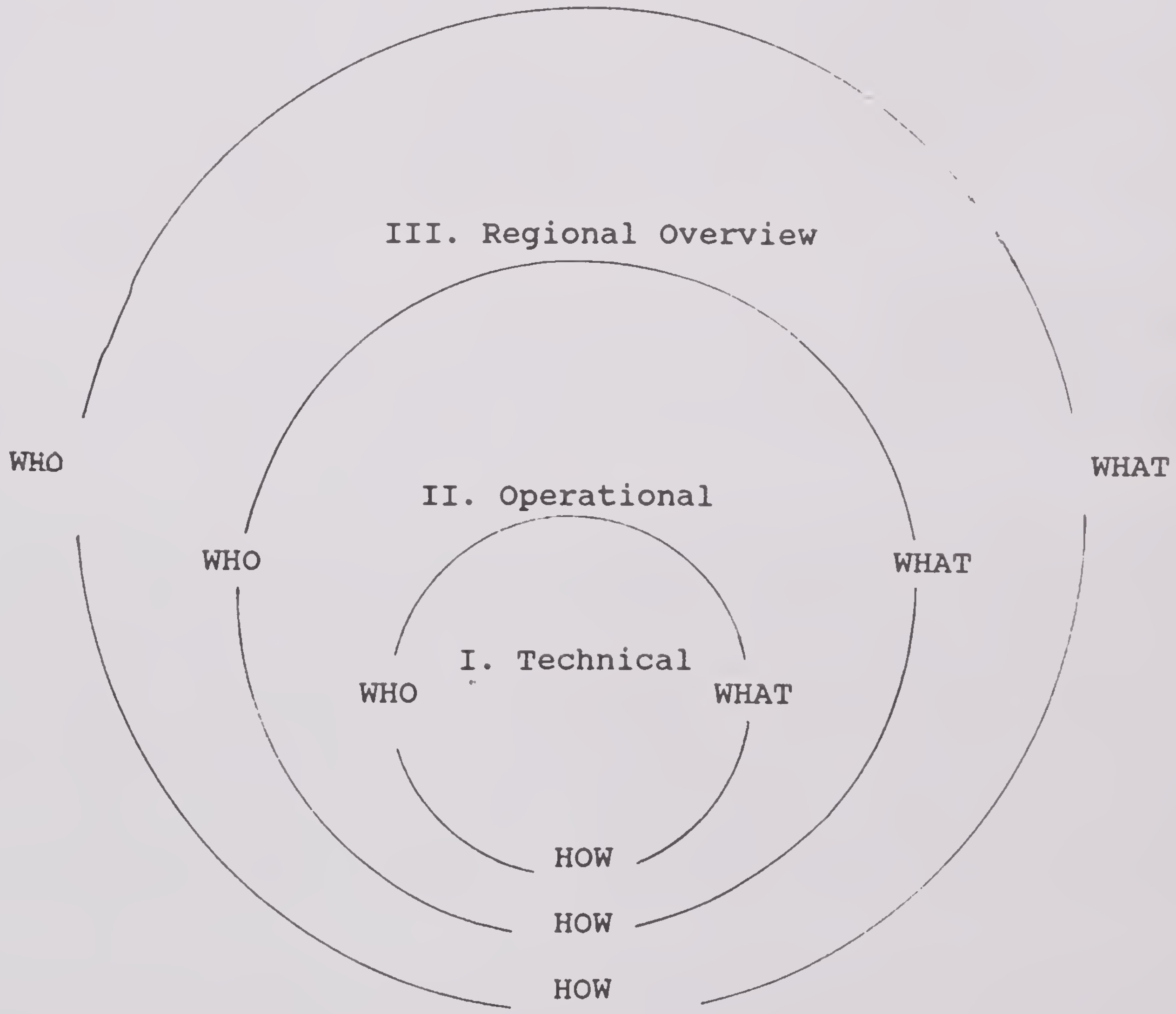


TABLE 3. CIRCLE I (TECHNICAL)

WHAT is to be managed?

- Dissemination of techniques (both natural scientific and socioeconomic) for generating information relevant to management of coastal erosion—i.e., information sharing and training.

OUTPUTS to local manager/marine scientist teams:

- Training opportunities in shoreline measurement and monitoring, forward modeling, decision making, and project development.

HOW? Using which tools?

- Guidebooks and manuals.
- Literature searches.
- Information transfer among case studies.
- Workshops and training courses (see below).
- Communication arrangements for participants—e.g., electronic mail.

WHO is to manage?

- IOCARIBE plus Program Coordinator, with Expert Group.
- Various experts on, for example:
    - geomorphology
    - management/decision
    - cost-benefit analysis
    - coastal zone laws
    - coastal peoples' sociology and economic bases

PROGRAM ACTIVITIES

TRAINING

Training is viewed as the cornerstone of this program. It is intended that learning in workshops and training courses be experiential as well as didactic. Although they would typically be led by experts, participants would be encouraged to present their own experiences in, for example, their particular case studies. It appears that practically all of the relevant courses can be led by members of institutions that have responded to the call for expressions of interest in the project. In this regard, institutions that have offered training to the project are identified in Table A-1, and some comments are also added with respect to those institutions submitting case study preproposals in Appendix B. The file containing full institutional responses to questionnaires is maintained at the IOCARIBE secretariat. Decisions on who should be involved in developing and delivering training courses are the responsibility of the Coordinator, aided by the Expert Group.

TABLE 4. CIRCLE II (OPERATIONAL)

WHAT is to be managed?

- Present or anticipated coastal erosion due to sea level movements in a potentially severe, high-priority situations in a particular country, at least to the stage of prefeasibility and choice of optimal response, given the existing constraints. (Design and construction of large, expensive engineeringworks would be beyond the scope of this program.)

OUTPUTS to local planning authorities:

- Opportunities for training of nonspecialists from government and NGOs involved in management courses in resource use planning, decision making and project development, and integrated coastal management.
- Case study report justifying a particular response option.

HOW? Using which tools and techniques?

The applicable techniques are:

- Identification of problems/opportunities.
- Generation of alternative options.
- Evaluation of alternative options.
- Choice among alternative options.

For most participants, training in this line of approach will be required.

WHO is to manage?

- The mechanism for achieving program goals at the operational level is the case study. It is anticipated that the local planning authorities would participate throughout the case study. The leader of the case study team would be a local manager, supported by marine scientists.

Arrangements for training will be handled by the Project Coordinator. She or he will deal with all logistical and financial arrangements with participants and host institutions, which will be selected from respondents (Table A-1) who have indicated willingness to provide facilities and support on a counterpart basis to the project.

Courses will be arranged in two cycles. In cycle 1, during project year 2 (Table 6), each of the five courses will be offered in sequence at three different locations to 15 people (per course). Courses may be offered in either Spanish or English, and the location will be determined by the Coordinating Group to provide for equal opportunity to potential participants on a regional basis, and will bear in mind the adequacy of support facilities offered by the institutions for training purposes.

TABLE 5. CIRCLE III (REGIONAL OVERVIEW)

WHAT is to be managed?

- Build-up of regional capability for management of coastal erosion due to sea level movements and other forcing mechanisms.

OUTPUTS to local planning authorities, to coordinators of regional programs (e.g., IOCARIBE, UNEP), to local manager/marine scientist teams:

- Training in resource-use planning and integrated coastal zone management.
- Quality control audits on case studies.
- Written reviews documenting relevant experience and techniques.
- Guidebooks for coastal planning.

HOW? Using which tools and techniques?

- Training in resource use planning.
- Training in integrated coastal zone management.
- Training on quality assurance and quality control audits.
- Symposia for case study team leaders.
- Final program symposium with published proceedings.

WHO is to manage?

- Program Coordinator with support of experts as consultants.

TABLE 6. PROGRAM IMPLEMENTATION SCHEDULE

ACTIVITY	1992		1993				1994				1995				1996				1997	
	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2
EXPERT GROUP MEETINGS	X	X		X		X		X		X		X		X		X		X		X
PROGRAM REPORTS				—				—				—				—				—
CONTRACT TRAINING INSTRUCTORS	—	—																		
INSTRUCTOR'S WORKSHOP			X																	
PREPARE TRAINING MANUALS				—	—															
INVITE PARTICIPANTS			—					—												
MAKE LOGISTICAL ARRANGEMENTS		—	—	—	—	—	—	—	—	—	—									
TRAINING COURSES					—	—	—	—		—	—	—	—							
REVIEW CASE STUDY PROPOSALS	—	—	—																	
CONTRACT FOR CASE STUDIES AS REVISED		—	—	—																
TEAM LEADER MEETINGS				X				X				X								
CONDUCT CASE STUDIES					—	—	—	—	—	—	—	—	—	—	—	—				
QUALITY CONTROL AUDITS						—				—				—						
INTERIM CS FINANCIAL REPORTS							—		—		—		—		—					
INTERIM CS REPORTS							—		—		—		—		—					
FINAL REPORTS																	—			
PROJECT SYMPOSIUM																		X		
EDIT AND PRINT TRAINING MANUALS			—	—	—	—														
FIND EXTERNAL PUBLISHER					—	—	—	—												
CONTRACT EDITING OF CASE STUDY VOLUME															—	—	—			
PREPARE REGIONAL GUIDEBOOKS													—	—	—	—	—	—		
EDIT & PUBLISH GUIDEBOOKS																			—	—
IOCARIBE NEWS	—		—		—		—		—		—		—		—		—		—	
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4

A second cycle of training will take place in project year 3. By this time, the courses will have been fine-tuned and will have benefited from the inputs of the case studies. This cycle will be aimed especially at countries and institutions that may not initially have been involved in the project, but that have been attracted to it by efforts of the Coordinating Group. The schedule for this cycle will be similar to cycle 1, except that site selection for course delivery can be varied, and the number of students per course reduced to 10, assuming that most of the technical institutions are involved in Cycle 1. Cycle 2 courses must make a concerted effort to incorporate government representatives, planners, engineers, and NGOs.

COURSE A: MEASUREMENT AND MONITORING

To begin the process of shore zone management, there is the question of whether a problem actually exists. The three steps in this process are:

1. To express the desired vision of the shoreline in, say, 2050, as held by the affected community.
2. To predict the evolution of the shoreline under the status quo management regime.
3. To identify any significant discrepancy between the vision and the prediction.

The most challenging objective here is to predict the evolution of the particular shoreline of interest. The techniques of shore process assessment and forward modeling are involved. Informal forward modeling is addressed here; formal forward modeling is addressed in Training Course C. Assessment and informal forward modeling will ideally include the following:

- Geological perspective (tectonics, structure, coastal sedimentary environments, stochastic vs. deterministic processes and relative importance).
- Subregional synthesis.
- Analysis of existing records of shoreline configuration—e.g., from series of aerial photos, maps, narrative evidence, and satellite imagery (e.g., LANDSAT, SPOT).
- Assessment of proximity to equilibrium configuration.
- Assessment of sediment budget via wave climate and nearshore currents' capacity for littoral drift, beach profile volumes.
- Regional overview, summary, and trends.
- Potential for changes (greenhouse scenario):
  - In shore configuration due to sea level changes
  - In wave climate due to sea level changes
  - In sediment source strength
- Importance of GLOSS and forward modeling of sea level changes, routine monitoring of sea level changes by tidal gauges and other methods.
- Informal prediction of future shoreline configuration.

Of course, a prediction of shoreline configuration has inherent uncertainties. These require quantitative evaluation. They imply that the choice among alternative options will be decision with risk.

After a remedial action has been implemented, the shore zone should be monitored in order to maximize learning. Monitoring can be accomplished at various levels of sophistication, from repeated land surveying to analysis of time series of aerial photos and satellite imagery. This task is less difficult than initial shoreline assessment and prediction of shoreline evolution, and involves identifying and measuring the essential subset of variables that will describe the effect of the dominant processes in interaction with the particular remedial action implemented.

Another topic that would be considered in this course is quality assurance/quality control for field observation programs in case studies.

COURSE B: FORWARD MODELING

The purpose of forward modeling is to predict, relatively inexpensively, but formally and mathematically, the evolution of a particular shoreline under conditions of status quo management and under various alternatives, including remedial options. Thus, modeling, in conjunction with field observations, can be useful in evolution-prediction and option-evaluation stages (Course D).

This course would present a series of modeling techniques, starting with simple approaches and then increasing in complexity. With each technique a process of verification, calibration, sensitivity testing, and validation would be attempted. Verification is the act of checking that all the most important processes are included and that the model reflects actual conditions with acceptable fidelity. Calibration is the act of setting parameter values so that model predictions approximate observations as closely as possible. Sensitivity testing explores the effect on predictions of uncertainty in parameter values. Where outputs are very sensitive to parameter values, further surveys or experiments may be justified in order to refine parameter estimates. Validation is the final check, where the comparison is made between model predictions and field observations not previously used for calibration.

COURSE C: RESOURCE USE PLANNING

In the process of identifying problems, generating alternative solutions, and choosing between them, opportunities will undoubtedly arise to suggest measures for improved resource management practices. These practices will most likely tend to be anticipatory, preventative, and relatively easy to implement. In many cases, they will require only a shortened version of the decision process normally required for rehabilitation problems.

This approach is based on the premise that appropriate planning for coastal development can significantly reduce negative human impacts on this zone, especially in relation to shoreline stability (e.g., Hendry, in press, a). It uses basic principles of understanding the function of coastal systems at various locations and integrating these more closely with the development process. Such approaches are uncommon in the region and can substantially mitigate the potential negative effects of future development and help to improve existing problem areas. This course will elucidate various preventative approaches. One set of guidelines that has emerged from experience is the following:

- Understand the natural beach system before it is altered.

- Develop a setback line before construction begins.

- Where possible, use soft solutions, such as sand nourishment, rather than hard solutions, such as sea walls.

- Maintain a prominent foredune ridge.

- Study the potential impacts of coastal structures.

- If the beach is valuable for tourism, recreation, or wildlife habitat, do not mine sand from the dunes, beaches, or nearshore.

- After a storm, do not drastically alter the beach.

At one level, examples of possible preventative measures are perturbing toward equilibrium beach configurations, sand management, and conservation of vegetation. A beach in equilibrium configuration will not lose sand laterally. Under a program of sand management, mining of beach sand would be controlled; sand overwashed onto a backshore roadway during a storm would be replaced on the foreshore. The public can be informed about how beach vegetation helps retain sand against aeolian and wave erosion—e.g., by using attractive, "cartoon" signage, which should make them less likely to destroy beach plants.

At a more regional level, one could consider the cost-effectiveness of "vulnerability indices" (e.g., Gornitz and Kanciruk, 1989; Hendry and Bacon, 1990). If the potentially vulnerable coast were surveyed, then a set of criteria could be established that, when coupled with the survey data, would identify those coastal reaches especially vulnerable to erosion or storm impacts.

The importance and applicability of Environmental Impact Assessment as a site planning tool will also be stressed, with particular reference to case studies and successfully using this procedure.

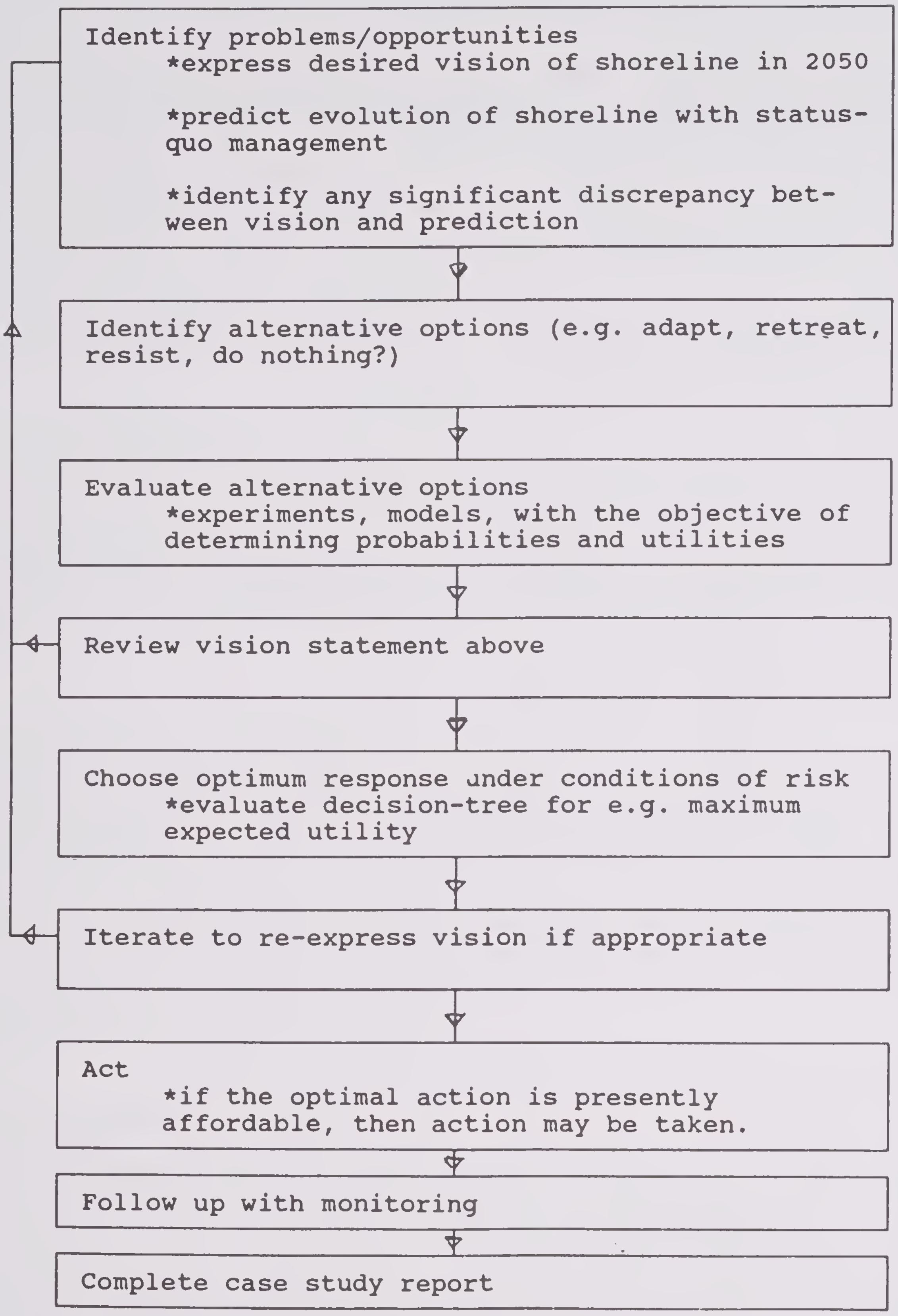
Course D: Decision Making and Program Development

Referring to Figure 5, once a coastal erosion problem is identified, there arises the need for a response. This course is concerned with methods for identifying, evaluating, and ranking alternative options, feasibility studies, and program development.

To generate options, consider the three main classes of response strategies: adapt, retreat, or resist. Table 7 identifies categories of decisions implying options in each category.

The process of evaluating these options can be interpreted, in a decision-under-risk framework, as meaning to determine utilities and (possibly) probabilities for favorable and unfavorable scenarios associated with each option. Utility or net worth of a particular option, including tangible and intangible aspects, can be assessed by using, for example, cost-benefit analysis. This requires the input of local people in practice.

FIGURE 5. DECISION-MAKING TREE



Identify problems/opportunities
*express desired vision of shoreline in 2050
*predict evolution of shoreline with status-quo management
*identify any significant discrepancy between vision and prediction

Identify alternative options (e.g. adapt, retreat, resist, do nothing?)

Evaluate alternative options
*experiments, models, with the objective of determining probabilities and utilities

Review vision statement above

Choose optimum response under conditions of risk
*evaluate decision-tree for e.g. maximum expected utility

Iterate to re-express vision if appropriate

Act
*if the optimal action is presently affordable, then action may be taken.

Follow up with monitoring

Complete case study report

Figure 4.3 Schematic for Erosion Management Process

Probabilities are derived or estimated from the scientific information, where required (see maximum criterion below). The probability of a given scenario may be assessed with the assistance of formal modeling (Training Course B). Of course, models exist at several levels, from informal/verbal to formal/mathematical. It will likely also be possible initially to estimate probability for a particular scenario based on the assessment of the system dynamics, the anticipated future configuration under the status quo management regime, and the collective experience with the option being considered.

TABLE 7. CATEGORIES OF DECISIONS THAT SEA LEVEL WILL INFLUENCE

LOCATIONAL DECISIONS

- WHERE TO PUT PRIVATE DEVELOPMENT AND REDEVELOPMENT
  - HOUSING
  - FACTORIES
  - RESORTS
  - ENERGY FACILITIES
  - HAZARDOUS WASTE SITIES
- PUBLIC DEVELOPMENT DECISIONS-ROADS
  - UTILITIES
  - PORT INFRASTRUCTURES
  - PARKS
  - BRIDGES
- PURCHASE OF LANDS FOR CONSERVATION

STRUCTURAL AND SITE DESIGN DECISIONS

- HOW TO BUILD FACILITIES
  - THEIR MOVABLILITY
  - SITE CONTOURING
  - CONSTRUCTION TYPE AND QUALITY
  - PLANNED LIFETIME OF STRUCTURE
- R&D ON HOW TO IMPROVE OPTIONS
  - SUCH AS MAKING STRUCTURES MORE "SEA LEVEL RESISTANT"
  - MAKING STRUCTURES MORE MOVABLE
- HOW TO MAKE LOW-COST DESIGN CHANGES TO REDUCE ADVERSE EFFECTS

PROTECTIVE MEASURES AGAINST FLOODS AND EROSION

- PROTECTIVE FACILITIES SUCH AS SEAWALLS
  - HEIGHT
  - TYPE
  - FOUNDATION SIZE (SO THEY CAN BE EXPANDED LATER)
- BEACH NOURISHMENT DECISIONS
- VEGETATION PLANTING AND MAINTANCE DECISIONS
- RIVER CHANNALING AND RECHANNELING DECISIONS
- LAND ACQUISITION AND SET ASIDE FOR PUBLIC AND PRIVATE WORKS FOR FUTURE PROTECTION
- LOCAL ZONING AND OTHER LAND-USE CONTROLS TO REDUCE DEVELOPMENT IN WRONG AREAS
- FLOOD PROTECTION REQUIREMENTS FOR HAZARDOUS FACILITIES

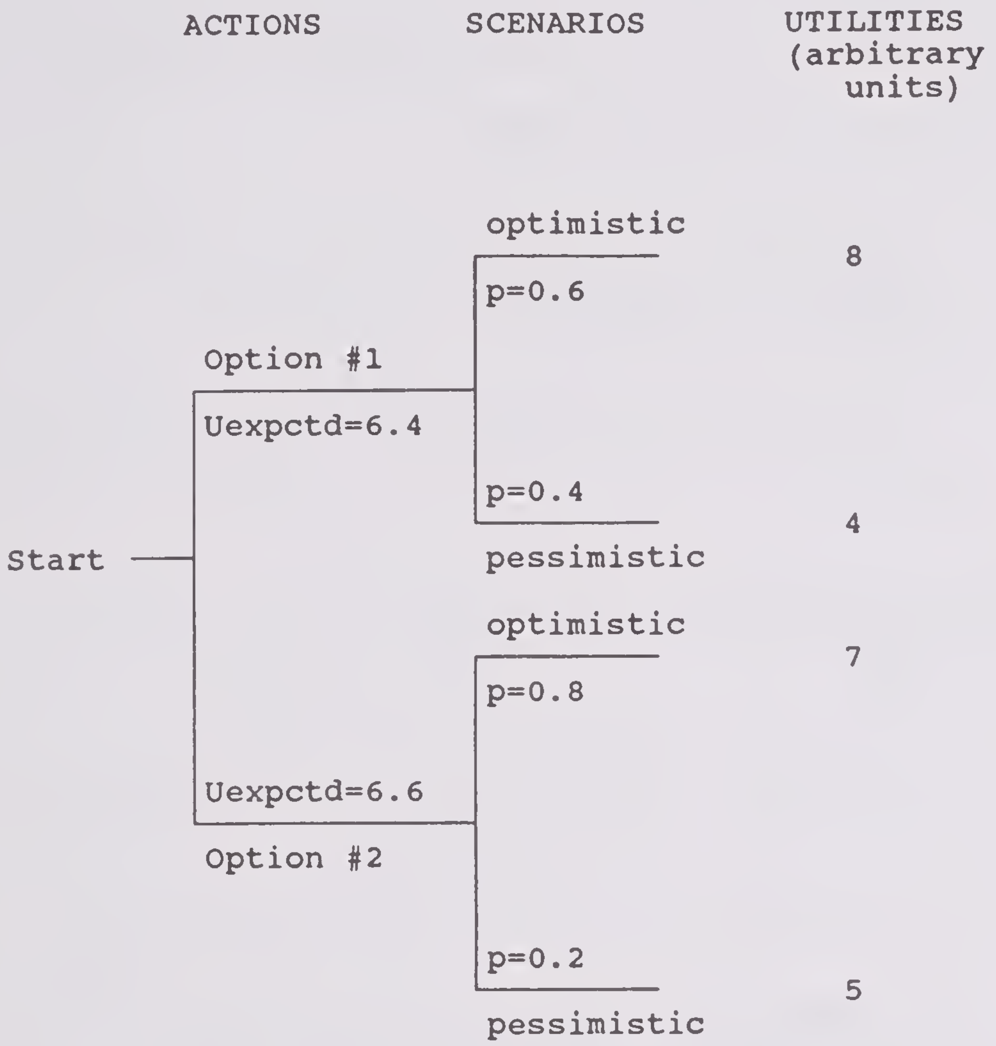
DECISIONS ABOUT FLOOD MITIGATION PLANNING

- EVACUATION PLANS
- POST-DISASTER PLANS
- INSURANCE POLICIES, SUBSIDIES, AND COSTS

Source: Hoffman et al., 1983.

In the decision-tree framework envisioned, the scenarios can be ranked in accordance with the resolving power of the information. However, if the utilities can be only roughly estimated and/or if the probabilities for favorable and unfavorable outcomes for a particular action are poorly resolved—i.e., close to 50–50, then the ranking of options by evaluating the decision-tree will not be satisfactory. In some cases, two options may rank equally high, and in others, even the highest ranked option may be judged too risky. In such cases, further studies—feasibility studies—to enhance resolving power may be considered (Figure 6). Furthermore, there is a decision-tree technique or estimating in advance the cost-effectiveness of proposed feasibility studies in terms of the value of the resulting enhancement of resolution. At this stage, with considerable insight gained into the merits of the various alternatives, it is worthwhile to review—revise if necessary—the vision statement.

FIGURE 6. HYPOTHETICAL DECISION TREE



Utilities and probabilities are supplies; the expected utilities are calculated. In this case, the options are not well resolved using the criterion of maximum expected utility.

Project development is another subject for consideration here. It refers, in this context, to the process of integrating and presenting the scientific and community socioeconomic information, such that decisions are approached in sequence and are soundly based (although probabilistic, with outcome not guaranteed). In this open, adaptive process, communities and governments may be expected to be more supportive of the case study. In addition, project development will refer to the use of scientific information to attract funding for further work. As an example, the Coastal Conservation Project Unit in Barbados took basic beach profile and coastal process information, assessed trends, attracted government concern and support in the light of measured erosion, obtained funding from the IDB for a Diagnostic Pre-Feasibility Study, then used the results of that work to obtain money from the same source for a feasibility study, now in progress. The next stage of this sequence will be project implementation.

COURSE E: INTEGRATED COASTAL MANAGEMENT

Integrated coastal management takes a wider view of coastal activities, opportunities, problems, and their linkages. Here the instructor would build awareness of, for example, the deleterious linkage between water pollution, reef degradation, and diminution of carbonate sand supply for nearby beaches, or the potential conflict between a proposed scheme to construct a causeway to a nearshore island, where the causeway interdicts a sediment flow, causing inundation of a reef with sand, and displacement of reef fishermen. Ecosystem modeling techniques would be discussed and used, including models for systems far from equilibrium and self-organizing (e.g., Allen and MacGlade, 1987). Potential inputs to the training program on this rapidly advancing technology can come from several project respondents (Table A-1). The Coordinating Group should be aware of interest expressed in a letter to the IOCARIBE Secretariat from Guy Engelen of the Research Institute for Knowledge Systems (RIKS), of Maastricht, The Netherlands.

CASE STUDIES

In their submissions indicating willingness to participate in this program, several institutions gave outlines of case study projects they wished to have funded on this program. IOCARIBE, through the Coordinator and Expert Group, will select a maximum of 10 studies for support and will work with team leaders to ensure integration of the overall program objectives in these studies prior to their implementation. IOCARIBE will, where appropriate, arrange for inputs to case studies from program participants from other institutions where it is felt particular skills and/or approaches will complement the local effort. The coordinator and Expert Group will ensure quality control on all projects.

Case studies must be developed to show the potential linkage between data collection, and decision-making and management interventions based upon the technical information. The project is set up to provide input to this critical area if required, through provision of advice in advance of case study implementation, expert participation from the professional resource pool within the larger project, and training in the various modules described in Figure 5.

All institutions submitting preproposals have committed counterpart contributions. The maximum support to be provided from IOCARIBE project funds is U.S. $10,000 per year for three years. The IOCARIBE Secretariat should have the power to withdraw funding support from institutions that are unable to fulfill commitments to financial and project progress reporting, or who otherwise fail to satisfy the Coordinating Group of the ongoing viability of their program.

Participants in case studies will be expected to submit regular reports on activities, to have team leaders participate fully in annual project meetings, and to submit full papers on the activity to the program symposium in year 4, for final publication in a special program volume.

Brief details of the case studies as proposed by the institutions are given in Appendix B. Of special interest is the spectrum of approaches and outputs covered by the proposed activities: the IOCARIBE project provides an ideal opportunity for the experiences in these different projects to be shared, by collaboration on case studies, through presentations at training programs, and through the final symposium and its outputs: a volume on case studies and development of regional guidebooks. This potential for mutual exchange and learning is a key feature of the project.

PUBLICATIONS AND INFORMATION DISSEMINATION

TRAINING MANUALS

These manuals will be developed for each of the courses outlined above. The Expert Group will work with the Coordinator to identify the most qualified people to develop these manuals, and to present the training courses. The manuals will be printed in both English and Spanish and will form part of a complementary series designed to begin with fundamental aspects of technical data acquisition, moving through modeling for future change, to decision making and project development, and finally integrated coastal zone management. Initial printing will cover the needs for training course participants and for other IOCARIBE representatives, but IOCARIBE may seek additional support from publishing houses to achieve wider dissemination of information should the demand appear to justify this.

CASE STUDIES

IOCARIBE will produce a volume containing the reports of all regional case studies, for printing and distribution to member institutions. It is anticipated that this volume will begin to be compiled during the workshop at the end of the case study period, and that final responsibility for editing and production will rest with the coordinating group. This group should seek the interest of one of the major journals in printing a special volume containing these results—e.g., *Journal of Shoreline Management, Journal of Coastal Research, Journal of Coastal Zone Management*, to achieve maximum effect.

GUIDE BOOKS

A major contribution to improved coastal development can be made by production of a book or books providing guidelines for coastal area planning and management in the Caribbean, with a target audience that should be primarily nonspecialist. Book of this nature already exist for the Gulf States and Florida ("Living With the Shore" series produced by Duke University), and these provide for informed decision making by potential property owners and developers in coastal areas. The needs for these books should be tailored to regional requirements, and the Coordinator and Expert Group will select and contract writers and editors from among project participants and ensure quality control of final products. The Coordinator and Expert Group will seek interest from a recognized publishing house for wider printing and distribution of these books.

PROGRAM MANAGEMENT AND IMPLEMENTATION

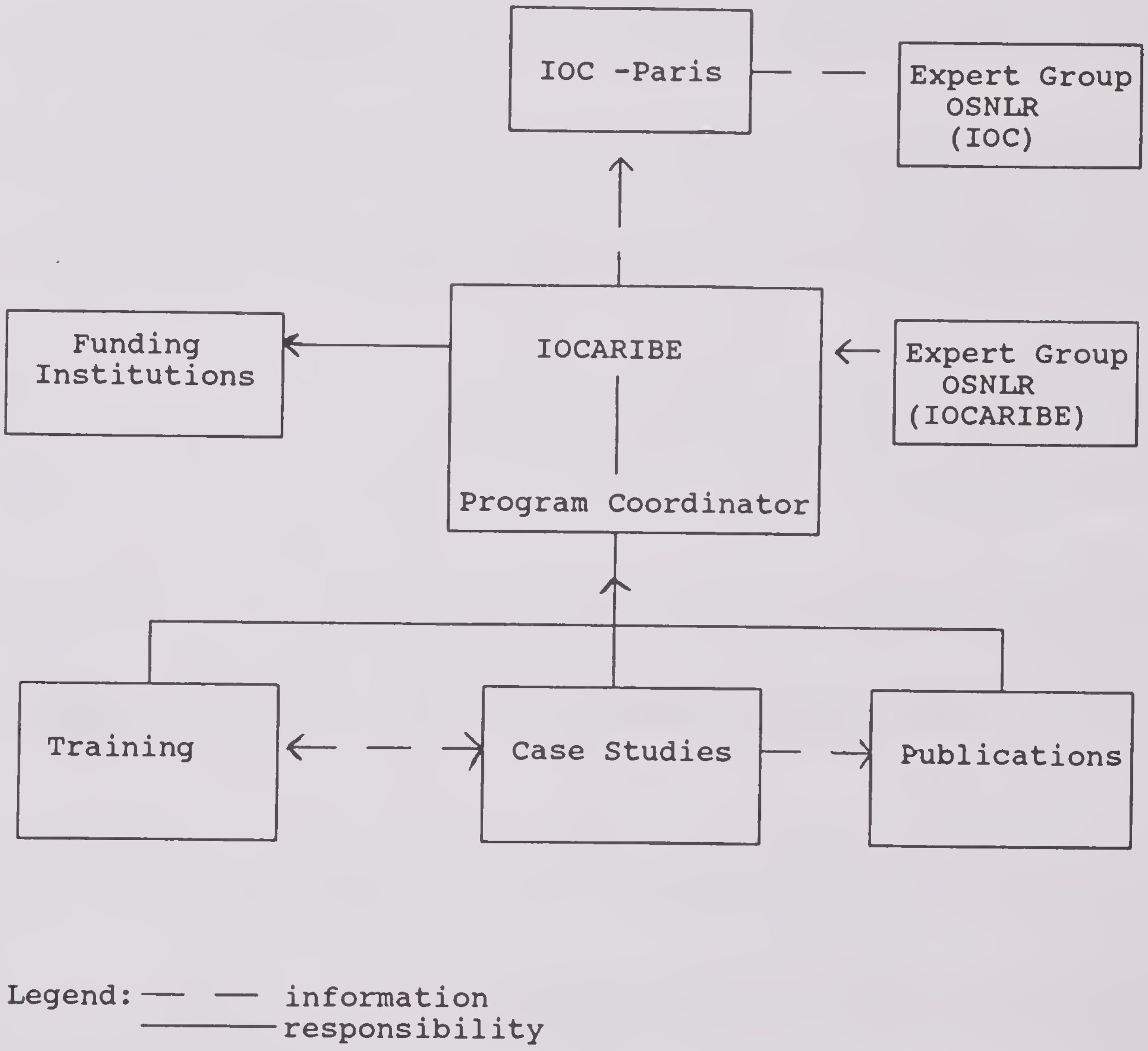
COORDINATOR AND EXPERT GROUP

The success of this regional program will depend on the effectiveness of a central coordination group, and of communications between it and participating countries. It is proposed that the IOCARIBE Secretariat will act as executors for contract management with funding agencies and with individual institutions. IOCARIBE will also have overall responsibility for program management and direction, including maintenance of project deadlines for activities and deliverables, and progress and financial reports to funding agencies. The Secretariat will be supported in this by appointment of a full-time Program Coordinator, and also an Expert Group on Nonliving Marine Resources. The Coordinator and Expert Group together form the Program Coordinating Group.

The Coordinator must be a person with regional experience, who will have a broad knowledge of the technical aspects of the programming defined in this proposal. It is desirable that the Coordinator have experience with project planning and coordination, and also be able and willing to travel regularly. The coordinator must be broadly acceptable to the institutions involved in the project, and possess the capability to provide leadership not just through sound management but through development of cordial relationships with coworkers and participating agencies. Responsibility for filling this key position should reside with the IOCARIBE Secretariat.

This expert group will be nominated by the IOCARIBE Secretariat, and will be composed of no more than six professionals with recognized capability in the areas of coastal management specified in above. A Program Organization Chart (Figure 7) is included to indicate the relationship between these groups.

FIGURE 7. PROGRAM ORGANIZATION CHART



The Program Coordinator, in conjunction with the Expert Group, will be responsible for decisions relating to selection of:

1. Locations for training sessions, workshops, and program meetings.
2. Instructors to develop course materials and deliver training programs, on contract for this work.

3. Case studies to receive financial support, and recipients of E-mail subscriptions.

4. Editors for special volumes and training manuals (Spanish and English).

This group will also:

5. Ensure maximum opportunity for representatives of regional governments and other agencies (including NGOs) to participate in training courses, case studies, and other activities, such that these are not for technical representatives alone.

6. Assist IOCARIBE in identifying additional funding to support participation in program activities not covered by the budget, as in the case of general workshops, for which IOCARIBE can support a limited number of participants.

7. Solicit recognized journals and publishing houses to publish training manuals, case studies, and regional guidebooks.

8. Have responsibility for assisting revision of case study programs to conform to the perspectives of the program.

9. Review program progress annually, and advise IOCARIBE of any changes required, and especially if these changes affect the MOU with external funding agencies.

10. Encourage participating institutions to use their offers of counterpart logistical and/or financial input to run field meetings either in association with or in addition to the existing meeting schedule, and arrange support/sponsorship from other regional/international programs and organizations for these activities.

11. Solicit and edit, where necessary, contributions to "IOCARIBE News" and other publications, for general information, as appropriate.

12. Design in association with regional working groups, guidebooks for coastal area developers and landowners, and arrange for preparation and production of these, in Spanish and English.

13. Contact, and draw into the program, IOCARIBE countries not as yet represented on the response matrix (Table A-1), and ensure that the appropriate training and other opportunities are provided to them.

14. Ensure that an effective, interactive dialogue is maintained with other regional research projects with whom data exchange and complementary programming are shared.

15. Solicit additional case studies, and vet these and any others that have been submitted after formulation of the original project proposal.

COMMUNICATIONS

This key component of the program will be maintained through a variety of mechanisms:

1. *Meetings.* The budget (Table 8) makes allowance for annual travel for the Program Coordinator, and the following meetings:

a. Expert Group/Coordinator. Biannually, except in Year 1, when substantial input to program development, and decision making on activities requires that this group meet on three occasions.

b. Team Leader meetings: Case Study leaders to meet annually with Program Coordinator in years 1–3, to ensure appropriate orientation, cross-linkage in methodology and results, and collaboration with other program activities.

c. Trainers: Each training module to be prepared by contributions from 3 persons, who will meet for a week to prepare manuals and training courses. Manuals to be prepared in two versions, English and Spanish.

d. Training courses: Each module will be held in three locations, representing English and Spanish-speaking territories. This allows for 15 workshops, with funding requested for 15 participants to each in Cycle 1 and 10 participants in Cycle 2. (This training schedule will be repeated in year 3, providing additional opportunity for as wide a participation as possible.)

e. Program Symposium: To take place in year 4, open to all program participants and interested parties, to present results of case studies and other project activities, and prepare initial drafts in working group sessions for the special publications on case studies, and on a regional guidebook for coastal management in relation to shoreline change.

2. Telecommunications: In addition to a central budget for fax, phone, and courier/postage for the Coordinator, budget allowance ins made for E-mail subscriptions for program participants, to enable routine information exchange, as an alternative to establishing a central program data center.

3. Publications: IOCARIBE produces a regular newsletter, which will be used by the Coordinator and Expert Group, plus participants, as a vehicle for routine dissemination of program news. All participants will be encouraged to contribute articles on this program to the numerous international newsletters and other media.

IMPLEMENTATION

The schedule for implementation is shown in Table 6. The program is scheduled to run for five years, with a suggested starting date of the third quarter of 1992. This starting date will be subject to approval of funding, and may need to be revised, dependent upon the funding cycles of the agencies that become involved. The program sequence follows a modular structure—training-case studies-publication.

FINANCIAL PROPOSAL

The emphasis in seeking funding for this program is in providing opportunity for managers and scientists involved in coastal management in the Caribbean to benefit from training and the exchange of ideas and information through training, project experience, workshops, and meetings. This objective is of fundamental importance in a region that shares common problems of coastal resource management, but in which communications and the opportunities for mutual exchange of information are restricted by financial and technical constraints.

A unique feature of the present proposal is that expertise for all the training identified and for developing case studies comes from within the institutions that have committed themselves to the program by submitting responses to IOCARIBE (Table A-1). Therefore, with appropriate levels of funding, IOCARIBE will be able to match the capabilities of those with skills to those requiring them, and will not have to contract outside services.

Similarly, all respondents who wish to undertake case studies have committed themselves to counterpart contributions in terms of staff time, logistical and technical support, and provision of space and facilities to assist training and workshop/meeting activities. Case study support will be used primarily to assist field work and activities related to acquisition of information and preparation/presentation of results and reports. This attitude is entirely consistent with the IOCARIBE approach to programming, where cost reduction is achieved by contributions in kind by hosts of participating institutions.

In addition, funding is not requested for activities of the Expert Group that will support program management. Approval for formation of this group, and funding for the same, will be provided by IOCARIBE to the IOC during the next IOCARIBE Sub-Commission Meeting in Mexico in October 1992. The anticipated level of funding for such a group from IOC is expected to cover most of the costs of their activities.

IOCARIBE recognizes the differing emphases of funding agencies, and the funding proposal allows for some flexibility in approach by separating activity areas into several components, including Training, Case Studies, Publications, and Coordination.

The basis for provision of this budget is:

1. That the program will be managed full time by a Coordinator, whose emoluments will be based on a rate of U.S. $5,000 per month for each of the five years. U.S. $6,000 per annum will be allowed for the Coordinator's travel.

2. Office costs will be supported, especially in the areas of communication, allowing amounts for telephone, mail, fax, and E-mail subscriptions (most of these to participating institutions), totaling $13,200 per annum.

3. Production of training manuals and delivery of classes will be supported by honoraria to instructors amounting to $2,500 per one week course delivered. For 30 course-weeks, this sum is $75,000.

4. Participant (including instructor) costs for attending workshops are based on an average travel cost of U.S. $350, and a daily subsistence allowance of $120 per person.

5. Case study projects will be supported to a maximum of $10,000 per annum for 3 years, for up to 10 projects, over program years 2–4 inclusive, totaling $300,000.

6. Estimates for publications are included in Table 8. It is expected that the Coordinating Group will solicit the interest of established publishing houses for wider dissemination of materials developed for training, case study reports, and regional guidebooks.

A summary of the budget is provided in Table 8.

TABLE 8. SUMMARY OF YEARLY REQUESTED EXTERNAL PROGRAM FUNDING SUPPORT (THOUSANDS OF U.S. DOLLARS)

YEAR	Coordinator			Training		CS	Pubs.	Totals
	Salary	Trv/Acc/Ofc		Honorar.	Trvl/Accom.			
1	60	6	13.2	15	129.2		28.2	251.6
2	60	6	13.2	15	129.2	100	0	323.4
3	60	6	13.2	15	108.4	100	0	302.6
4	60	6	13.2	15	97.8	100	10	302.0
5	60	6	13.2	15	77.8		10	182.0
Total	300	30	66.0	75	542.4	300	48.2	1361.6
						Contingency		136.2
						GRAND TOTAL		1497.8

Counterpart contribution

Financial support is anticipated from the following sources (estimates):

1) IOC - for the Expert Group, 15- 20.000 per annum	US$100,000
2) Participating institutions - facilities and logistics, 30 workshops at 1.500 per week	US$ 45.000
3) Participating Institutions - salary and support for Case Studies (Appendix 8.2)	US$486.000
TOTAL	US$631.000

ACKNOWLEDGMENTS

This program proposal has been prepared on behalf of IOCARIBE by Malcolm Hendry, University of the West Indies, Barbados, and Ronald Loucks, Loucks Oceanology Ltd., Halifax, Canada, with valued advice from Fernando Robles and Anders Alm of IOCARIBE, and financial assistance from the International Center for Ocean Development (ICOD), Halifax, Canada. IOCARIBE gratefully acknowledges the support of ICOD, and also recognizes the significant contributions made by regional institutions in assisting proposal development.

Inquiries regarding involvement in the program, through provision and funding support or participation, should be sent to:

IOC Senior Assistant Secretary for IOCARIBE
Apartado Aereo 1108
Cartagena de Indias
Colómbia

Telephone and Facsimile: (57) (53) 650395
Telex: 37743 CNT CO (ATTENTION IOCARIBE)
TELEMAIL: (OMNET) IOCARIBE.SEC

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APPENDIX A

SAMPLE REGIONAL COASTAL RESOURCE MANAGEMENT PROGRAMS IN THE IOCARIBE REGION

IOCARIBE recognizes that other similar regional resource and environmental management programs may be on stream. This listing is of major projects of which it is aware. Country-specific projects have not been incorporated.

1. **CFRAMP:** Caribbean Fisheries Resources Assessment and Management Program. This 8-year project sponsored by the Caribbean Community (CARICOM), Canadian International Development Agency (CIDA), and International Center for Ocean Development (ICOD), provides CARICOM member states with the necessary information and institutional capability to manage and develop their own fishery resources. The Coordinating Unit is based in Belize, where a Resource Assessment United (RAU) will also be established for lobster and conch. Project startup is 1991. Linkage between IOCARIBE and this project needs defining, but CFRAMP will likely be most interested in management options/decisions that impact fisheries, habitats and landing sites.

2. **ENCORE**: Environment and Coastal Resources Project. This project is funded by the United States Agency for International Development (USAID), and is run through the Organization of Eastern Caribbean States (OECS), Natural Resources Management Unit (NRMU), located in St. Lucia. This six-year activity commences in 1991 with a six-month consultative process, where regional governments, institutions, professionals, NGOs, and other professional and lay persons will be asked to assist in the clear definition of coastal areas and issues requiring priority management within the OECS member countries. Project concept planning allows for two major levels of activity: regional programs and site-specific programs. Regional programs will most likely focus on standards for coastal water quality, building on existing institutional capacity (see CEHI, below), and other activities, such as development of marine parks. Site studies will be more detailed, integrated programs, looking at a wide range of coastal management issues. Discussions with the USAID ENCORE Project Manager and Branch Chief in Barbados indicate significant potential for interaction, given the nonliving resources focus of the IOCARIBE program, plus the training potential it provides in key areas.

3. **CARICOMP**: Caribbean Coastal Marine Productivity Project. After several years' effort, this project, a joint venture of regional research institutions with special interests in living resources, has just received significant funding from the MacArthur Foundation. The project seeks to standardize approaches to measurement and monitoring in coastal ecosystems (mangroves, sea grasses, and coral reefs), and to characterize the nature of nutrient flows between these systems. CARICOMP monitoring includes a range of features—e.g., physical oceanographic data, such as temperature and salinity. There appears to be great potential for collaboration in date exchange between CARICOMP and the IOCARIBE projects.

4. **IMPLICATIONS OF CLIMATIC CHANGES IN THE WIDER CARIBBEAN**: This joint United Nations Environment Programme (UNEP)/IOCARIBE task team was established through the Regional Coordinating Unit of UNEP in 1987 to evaluate regional problems relating to future sea level rise. The team's work is essentially completed, with preliminary reports published (UNEP, 1988, 1989 b), and with the final project presently being edited for publication by Edwin Arnold Publishers. From the view point of the present IOCARIBE initiative, this project has been valuable in highlighting areas of the region that may suffer greatest land-loss impacts due to sea level rise, and the resulting social and economic problems that will have to be faced.

5. **MARINE PARKS PROJECT**: Funded by the International Center for Ocean Development (ICOD) through the Caribbean Conservation Association (CCA), this project will assist CCA's initiatives in marine resources management through protected/controlled approaches to coastal areas, especially reefs and related habitats. Commencing in 1991, this project responds to wishes of regional governments for assistance in developing the framework for park management and also for identification of sites and planning for site management at specific locations. There is substantial potential for the IOCARIBE project to have outputs that will be of value to the CCA program, both in training and in incorporating considerations of longer-term physical change in shorelines with management of living marine resources.

6. **IPID**: Integrated Planning and Institutional Development. Due to commence in 1991, this project, funded by the Swedish International Development Agency (SIDA) through the UNEP office in Jamaica, will assist regional efforts at upgrading institutional capacity in marine and coastal area resource management, through development of appropriate legal, administrative, policy, and technology frameworks.

7. **NRDP:** Natural Resources Database Project. This two-phase project, funded by the Canadian International Development Agency (CIDA), involves (a) acquisition at 1:10,000 scale of aerial photography for ten Windward and Leeward islands (with limited coverage at 1:4,000), and (b) provisions of training and technical assistance to these countries for optimal utilization of the photography in natural resources inventory, assessment, and planning (Hendry and Hildreth, in press). Not only is there potential for linkage in the training, but the new photo provides an excellent opportunity for time-series analysis of eastern Caribbean shorelines in the project, using digital or other techniques, and incorporating previous series of coastal aerial photography that go back in some instances to the 1940's.

8. **CEHI**: Caribbean Environmental Health Institute. Based in St. Lucia, this organization is responsible to member governments of the Caribbean Community (CARICOM) in the area of environmental health. Primary activity areas include (a) development of effluent guidelines and water quality criteria in the CARICOM member states, (b) monitoring of nutrients, heavy metals, pesticide residues, polychlorinated biphenyls, and sanitary water quality using bacteriological indicators, for Commonwealth Caribbean nations. New programs are being implemented in these countries for complementary monitoring of mangrove and reef ecosystems in these countries. CEHI is committed to this IOCARIBE proposal, and there is substantial potential for information and data exchange.

9. **CEPPOL**: Marine Pollution Assessment and Control Program for the Wider Caribbean Region. This joint UNEP/IOC program links regional research institutions with capability in coastal and marine water quality measurement and pollution measurement capabilities. Its objective is to address eight areas of major concern in regional marine pollution and the proposed control measures to be taken. Begun in August 1990, this project will run for at least four years.

10. **EASTERN CARIBBEAN COASTAL MONITORING PROGRAMS**: This UNESCO activity, part of the COMAR project, has sponsored the development of a beach monitoring program for the islands of the eastern Caribbean (Cambers, 1991). Using basic measurement techniques and training of government representatives to allow for collection of data, this program seeks to provide baseline information on the stability of critical beach areas, to assist planning and conservation measures. The project is moving toward being institutionalized, to improve data storage, networking, technical advice, and program expansion. In responding to the IOCARIBE proposal, the consultant on this project indicated that by 1992, if institutionalization takes place, the project could be involved more fully in the IOCARIBE program, and the Coordinating Group for the IOCARIBE project should make every effort to maintain contact, as there will be many areas of mutual interest from which experiences can be shared.

APPENDIX B

DESCRIPTIONS OF CASE STUDY PROPOSALS

This section summarizes salient features of the preproposals submitted by respondents to the IOCARIBE questionnaire, sent to regional research/coastal management institutions. Budget is broken down into (1) institutional counterpart contributions—funds committed by the participating agencies in cash or kind; and (2) external—funds requested from IOCARIBE through this project. Full Preproposals are held at the IOCARIBE Secretariat in Cartagena, Colómbia. Total external support allowable was proposed at U.S. $10,000 per year for three years.

BARBADOS: Coastal Conservation Project Unit (GOB), CERMES, Univ. West Indies and Bellairs Research Institute of McGill Univ.

Goal: Identify parameters required to input for decision making on southeast coast of Barbados.

Objectives: Through ground survey, shoreline monitoring, aerial photography (historical), and land-use planning assessment, obtain understanding or shoreline changes and controlling parameters, relate these characteristics to long-term planning and project development decisions. and assist the government in developing a long-term strategy for development of this reach.

Outputs: Preliminary shoreline management plan, plus model of shoreline change and key controlling parameters.

Budget:	Institutional: 13 1/2 man months, est.	U.S. $20,250
	External:	U.S. $29,100

Consultants' Comments: The CCPU has an excellent track record of using basic scientific data to stimulate political and large-scale external support for coastal management programs, such as the present IDB-funded feasibility study on coastal management for the south and west coasts. This project extends the prefeasibility scoping to another area of the coastline, and is representative of the approach required in the IOCARIBE proposal. CCPU's experience in shoreline monitoring and project development plus decision making will be valuable in the training programs. The combined experience of the CCPU, CERMES, and Bellairs will also greatly facilitate training activities in resource use planning and integrated coastal zone management.

CAYMAN ISLANDS: Natural Resources Unit.

Goal: Establish a basis for evaluating stability or erosion of the physical structure of coral reef affected by bleaching phenomenon. Data to be used to predict consequences for coastline integrity, and strategy planning for coastal management.

Objectives: Monitor parameters responsible for mass bleaching. Correlate T, S, irradiance, current speed and direction with bleaching observations to allow prediction of future events and of loss of key species in the reef system.

Expected Outputs: Ability to predict long-term impact of bleaching on reef system, with estimation of rate of erosion, with inputs of this to future coastal management action/legal decisions.

Budget: Not specified.

Consultants' Comments: It is not clear where this project fits in the IOCARIBE program for shoreline change. While damage to reef is of course important in influencing coastal hydrodynamics and sediment supply, there is nothing in the proposal to indicate how such evaluations will be attempted. As it stands, this proposal could not receive support from the IOCARIBE project, but the aspect of reef degradation is important and should be developed by encouraging linkage with the University of Maryland (below) whose case study proposal for the Caymans is closely aligned with the project goals.

COLOMBIA:

1. Centro de Investigaciones Oceanográficas e Hidrográficas, Cartagena.

Goal: For three priority areas—Turbo, on the Gulf of Uraba; Sinu River, Gulf of Morrosquillo; coastline of Cartagena—understand geological and oceanographic processes in these eroding locations to understand controls required for conservation and management.

Objectives: Collect and interpret climatic, oceanographic, and geological data, complemented by aerial photography and SPOT imagery; understand dynamics of shoreline erosion; and improve professional skills in data analysis and interpretation.

Outputs: Definition of programs and approaches that can be used to inform national planning for the coastal zone, plus increased capability in data analysis.

Budget:	Institutional:	U.S. $257,711
	External:	U.S. $10,000 per year, Total U.S. $30,000

Consultants' Comments: This project promises to provide a good example of how the IOCARIBE program should function. CIOH wishes to use methods that it indicates are not well developed in-house, and the proposed training modules will provide the ideal platform to assist its program, especially in monitoring and remote sensing. Joint programming with institutions that are involved in the project and that have demonstrated expertise in this area is recommended. The budget includes a sum for training, which is being sought under another head on the project proposal. The link between collection of scientific information and its applications to decision making is not well developed.

2. Instituto Nacional de Investigaciones Geológico-Mineras (INGEOMINAS), Bógota.

Goals: Determine the behavior of sea level in recent geological time, and try to predict future changes.

Objectives: Quantify the rate of coastal change, identifying vulnerable areas that may be lost based on retrospective analysis of prehistorical and historical shoreline changes, using radiometric, offshore bathymetric, tidal gauge, and aerial photographic information.

Expected Outputs: Final report, graphics on trends of erosion, maps of vulnerable coastal areas, graphics of sea level correlation.

Budget:	Institutional:	U.S. $20,158
	External:	U.S. $19,666

Consultants' Comments: It is not clear how much of the coastline is to be covered, though the geological and historical approach will be especially useful in an area with active coastal tectonics, that have the potential to influence future sea level changes. The proposers should be aware of the free radiocarbon dating facilities under IGCP Project 274. It is not clear how the basic scientific information will be translated into a tool for decision making and management.

3. Universidad EAFIT, Medellin.

Goal: Implementation of a Geographical Information System to develop geological references for the quantification and magnitude (distance, rate of erosion) of changes in the coastline.

Objective: Development of a mapping data base in scale 1:25,000 for the projection and monitoring of changes in the Caribbean coast of Colombia through data from historical maps, remote sensing, identification of critical areas, and interpretation of collected data. The updated data base could be used to analyze changes in space and time of the coastal line.

Expected Outputs: Not specified.

Budget: Not specified (assumed external support of up to U.S. $30,000 is required).

Consultants' Comments: EAFIT submitted two proposals that are essentially the same (GIS), but without budget. Only one project needs support, but the use of the GIS in decision making needs clearer definition—the idea of layering a composite data base for the coastal area is inherently interesting, but the GIS will only present data, and not interpret it. EAFIT appears to have all the necessary hardware and software for the program, and should be encouraged to develop this project with inputs from other Colombian participants.

CUBA: Instituto de Oceanología, Havana.

Goal: To make a sediment budget and a characterization and quantification of the submarine sand sources on the shelf for the beach system, and monitoring variations on the beaches of the northern coast of Cuba and their relations to sea level rise.

Objectives: Zone and characterize ecosystems producing sand on the continental shelf of Micacos, Varader; identify the principal basins of sand on the shelf, and evaluate the possibilities of using them as sources for beach nourishment. Establish a monitoring network for morphological changes of the beaches of northern Cuba.

Expected Outputs: Concrete recommendations for the exploitation of sand in the submarine basins to be used in beach nourishment; recommendations for sound use and conservation of sand-producing ecosystems, with results published and discussed at the regional level.

Budget:	Institutional:	U.S. $20,000
	External:	U.S. $10,000 per year, Total U.S. $30,000

Consultants' Comments: The Institute of Oceanology has a splendid record of applying good coastal/marine science to real problems of shoreline maintenance, through programs similar to the one proposed here, including beach renourishment projects, and are used to multidisciplinary research. The proposal will need minimal modification. The institute has a substantial contribution to make to the training program, through presentation of its work on planning and implementation of beach renourishment.

FRANCE: Laboratoire CIBAMAR, University of Bordeaux.

Goal: Through collaboration (Colómbia—VIOH, Cartagena, University EAFIT, Medellin; Venezuela—Universidad Simón Bolívar; Cuba—Academia de Ciencias) be involved with measurement and monitoring of shoreline changes, and interpretation of sea level changes related to oceanic processes.

Objectives: Not specified.

Expected Outputs: Assist management of shoreline changes.

Budget:	Institutional:	U.S. $32,500
	External:	U.S. $101,000

Consultants' Comments: The University of Bordeaux has a long and successful history of interactive coastal area research in the Caribbean. The Coordinating Group for the project should encourage the University to more clearly define specific case studies and the proposed institutional linkages within the region. In addition, requests for external support must be brought into line with the proposed ceiling of U.S. $10,000 per year for three years. The University of Bordeaux can greatly assist the oceanographic and remote-sensing components of the training program.

GUYANA: Faculty of Technology, University of Guyana.

Goal: Set up coastal automatic tidal gauges to study tides and changing mean sea level.

Objective: To protect valuable land areas that are below mean sea level.

Expected Outputs: Economical sea-defense programs.

Budget: Not specified, except "limited human (and local financial) resources." Estimated required input of U.S. $30,000.

Consultants' Comments: Capability to measure sea level in a country where 90 percent of the population lives within 5 km of the coast, much of the land being below sea level, is intrinsically important and interesting. This proposal requires further development, and the Coordinating Group should put the University of Guyana in touch with George Maul (IOCARIBE Vice-President) at NOAA in Miami, where there is major commitment to the GLOSS project in the Caribbean (see below). Clearer specifications of the link between tidal gauges and "economical sea defense programs" are also required.

PUERTO RICO: Department of Marine Sciences, University of Puerto Rico.

Goals: Develop comprehensive knowledge of past shoreline changes; develop ability to predict future change in relation to changing hydrodynamics and sea level.

Objectives: Develop coastal classification, using hydrodynamic, geological, and shoreline change indicators; measure rates of change from aerial photos; select 15 sites for beach monitoring; model expected shoreline changes using wave refraction program for a 40-year sea level rise at projected rates of change, and determine reasonable 40-year set-back limits.

Expected Outputs: Comprehensive coastal classification; definitive estimates of rates of change; predictive ability for changes on eroding shorelines; inputs of quantitative analysis to legal program for managing setback limits.

Budget:	Institutional Support:	Faculty salary, software, lab. equip., computer time, etc.
	External:	U.S. $10,000 per year for 3 years, Total U.S. $30,000 (for fieldwork).

Consultants Comments: This program is fully in accord with the project concept. They mention possible links with the U.S. Geological Survey; these must be developed, as the USGS and Duke University have already digitized aerial photos to calculate historical rates of change for the whole shoreline. There is no need to duplicate that work in this program. UPR can make a contribution to training activities in oceanography and coastal science.

TRINIDAD AND TOBAGO: Institute of Marine Affairs.

Goal: Understand the dynamics of coastal changes in Cocos Bay, east coast of Trinidad, in an area that supports diverse economic activities.

Objectives: Using standard methodology, assess the hydrodynamics and sediment transport and accretion/erosion characteristics of the shoreline, allied to training for the research team in aspects of coastal management and engineering, remote sensing, and decision making.

Expected Outputs: Research reports and scientific presentations.

Budget:	Institutional:	Salaries and equipment (est. U.S. $20,000)
	External:	U.S. $10,000

Consultants' Comments: The proposal provides valuable opportunity for achievement of the IOCARIBE goal: linking on-site studies with project expertise and training. The work is basic coastal science, and the IMA will clearly benefit from inputs out of other project areas. Linkage or collaboration with other participants should be encouraged, and involvement in the training courses will also be required for the improvement in decision-making capability.

UNITED STATES:

1. National Oceanic and Atmospheric Administration, Atlantic Oceanographic and Marine Laboratory, Miami.

Goal: Determine the sources of climate-induced eustatic sea level changes from measurements of coastal relative sea level, tidal-gauge geodetic position, wind forcing, and deep-water steric anomalies.

Objectives: Create an autonomous sea level/weather observing system for the Intra-American sea; provide these environmental data in real time to interested organizations; conduct geodetic ties of sea level/weather stations to global network; relate measurements to coastal zone management.

Expected Outputs: Tools for coastal zone and economic growth management, including training of local personnel.

Budget:	Institutional:	PI Salaries (est. U.S. $50,000)
	External:	Sea level/weather station, U.S. $25,000, plus travel and support staff salaries (est. U.S. $15,000), Total U.S. $40,000

Consultants' Comments: This cutting-edge research will assist solution of one of the most complex issues in sea level/coastal studies: resolution of actual climate change signals from other background in sea level records. The IOCARIBE project should be a major user of sea level results, especially from the GLOSS program with which the NOAA proposal is intimately tied, and every effort must be made by the Coordinating Group to integrate the NOAA team and its GLOSS data base in local case studies, through establishment of clear lines of communication (e.g., the proposed E-mail subscriptions). This subject area should also be covered in Training Course A. The budget for this proposal (higher than the suggested ceiling) and for incorporation of the sea level data base network in the IOCARIBE program will need to be discussed by the Coordinating Group.

2. United States Geological Survey, Branch of Atlantic Marine Geology (BAMG), Woods Hole, Massachusetts.

BAMG has offered its extensive experience of coastal monitoring and shelf mapping to assist the overall goals of the project. BAMG has experience of Caribbean research in these subjects in several locations, most recently Puerto Rico, where it has a major post-Hurricane Hugo program under way. Special areas of interest to this project are BAMG's capability in:

a. Documentation of shoreline changes: BAMG has developed software for removing distortion from aerial photographs, calculating coastal changes between different sets in a time series, and classifying different types of coastline.

b. Quantification of beach changes: Using laser-driven Total Station survey equipment (Geodimeter), which is located using GPS, linked to custom-designed computer software, beach surveys, including inshore area, can be conduct in a time-effective fashion with near real-time outputs of profiles, contour maps, and three-dimensional surfaces. Computation of changes between intervals can then be achieved using the software.

c. Hazard assessment of maps for coastal areas. These are produced by incorporation of results from a and b, plus information on local geology, overwash potential, etc.

Consultants Comments: It is recommended that the BAMG resource group be used flexibly to assist with local case studies and with training programs for measurement and monitoring, resource use planning, and forward modeling. Several aspects of the various case studies (hazard maps, shoreline change measurements, etc.) are fairly common, and the coordinating group should identify finds from the case study budget to allow BAMG input at different locations, and also incorporate them in the training sessions.

3. Laboratory for Coastal Research, University of Maryland.

Goals: Define the physical and socioeconomic impacts of sea level rise, and examine the response and mitigation strategies required for three Caribbean islands—Grand Cayman, Barbados, and Antigua.

Objectives: By application of a custom-developed videomapping technique, using GPS, plus ground truthing and population and land-use indicators, determine which areas of the islands are at greatest risk from future sea level rise impacts, and make appropriate recommendations for planning. Develop impact scenarios for other Caribbean islands with similar characteristics.

Expected Outputs: Planning/management information for use by local and regional agencies and governments on possible impacts of sea level rise.

Budget: Institutional: U.S. $66,000
External: U.S. $30,000

Consultants' Comments: This program is highly complementary to others proposed in these case studies, and extends the range of forward modeling techniques brought into the program. The University of Maryland should be asked to consider linkages in Cayman with the Natural Resources Unit (see above), and in Barbados with the CCPU/CERMES group (see above). The University should also consider that Barbados and Antigua are rather similar in characteristics, both medium-elevation, mainly limestone islands characterized by compartmentalized pocket beaches with a carbonate sediment budget. For purposed of contrast, it would be better to leave out, say, Antigua, and choose instead one of the Windward islands, where mountainous terrain, narrow shelves, and terrigenous sediment supply are dominant. The University of Maryland group can make a contribution to training in monitoring and modeling.

Institutional response to the questionnaire circulated by IOCARIBE to potential project participants.
Y = yes
n = no
? = Insufficient data
space = No information

	IDENTIFICATION OF PROBLEMS				INSTITUTIONAL INVOLVEMENT								INSTITUTIONAL CAPACITY											TRAINING Offered/Needed	CASE STUDIES				
COUNTRY/INSTITUTION	- Coastal Land Loss	- Effective Control	- Adequate Technically	- Adequate Managerially	- Broader Activities	- Host Workshops	- Counterpart Support	- Counterpart Funding	- Case Study	- Ocean. Research	- Shoreline Res.	- Foreward Modelling	- Field Instruments	- Lab. Instsic Instruments	- Logistic Support	- Water Qual. Monitor	- Shoreline Monitoring	- Reef/Mangrove Montg.	- Oceanography	- Remote Sensing	- Foreward Modelling	- Resource Use Planning	- Coastal Zone Mgt.	- Measurement/Monitor - Resource Use Planning - Foreward Planning - Decision-making/Managt. - Integrated C.Z.M.	- Scientific Data	- Monitoring	- Modelling	- Relevance to Project	- Tool for Decision-Making
BAHAMAS																													
Water and Sewage Corporation					Y																								
BARBADOS																													
Coastal Project Unit/CERMES, UWI	Y	N	Y	Y	Y	Y	Y	N	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y/YY/NN/YY/YY/N	Y	Y	Y	Y	Y
CAYMAN ISLANDS																													
Natural Resources Unit		Y		Y	N	?	Y	N	Y	Y		N	Y	Y	Y	Y		Y	Y	?	N	Y	?	Y/YN/YN/YN/YN/Y	Y	Y	N	N	Y
COLOMBIA																													
Ingeominas, Bogota					Y	N	Y	Y	Y	N	Y	N	Y	Y	Y	N	Y	N	N	N	N	N	Y	/Y /Y /Y /Y /Y	Y	Y	N	Y	?
University EAFIT, Medellin					Y	Y	N	N	Y	N	Y	N		Y	Y	N	N	N	N	Y	N	N	N	/Y /Y /Y /Y /Y	Y	N	N	N	Y
CIOH, Cartagena	Y	N	N	N	Y	Y	Y	N	Y	Y	Y	N	Y	Y	Y		Y		Y	Y	N			N/YN/YN/YN/YN/Y	Y	Y	N	Y	Y
COSTA RICA					Y																								
CUBA																													
Institute of Oceanology	Y	Y			Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	?	Y	N	Y	Y	Y	Y/YY/Y Y/YY/Y	Y	Y	Y	Y	Y
FRANCE																													
CIBAMAR, Univ. Bordeaux (collaborative work in Colombia)	Y				Y	Y	Y	Y	Y	Y	Y		Y	Y	Y	Y	Y	Y	Y	Y		Y	Y	Y/NY/N Y/N	Y	Y		Y	Y
GUYANA																													
University of Guyana	Y	?	N	?	Y	Y	Y	N	Y	Y	Y	N	N	N	N	N	N	N	N	N	N	N	N	N/YN/YN/YN/YN/Y	Y	Y	N	Y	Y
JAMAICA																													
Marine Science Center, UWI	Y	N	N	N	Y	Y	Y	N	N	N	N	N	Y	Y	Y	Y	N	Y	Y	N	N	Y	Y	N/YY/NN/YN/YY/N	N	N	N	N	N
MEXICO					Y																								
PUERTO RICO																													
Dept. Marine Sci., Univ. Puerto Rico	Y	N	N	N	Y	Y	Y		Y	Y	Y	Y	Y	Y	Y	N	Y	N	Y	Y	Y	Y	Y	Y/N Y/Y Y/Y	Y	Y	Y	Y	Y
ST. LUCIA																													
Carib. Envir. Health Institute	Y	N	N	N	Y	Y	N	N	N	N	N	N	Y	Y	Y	Y	N	Y	N	N	N	Y	Y	N/YN/YN/YN/YY/Y	N	N	N	N	N
SURINAME																													
Geological and Mining Service					Y				Y																				
TRINIDAD AND TOBAGO																													
Institute of Marine Affairs	Y								Y	Y	Y		Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y		Y	Y	N	Y	Y
U.S.A																													
NOAA/AOML, Miami	Y				Y	Y	Y	N	Y	Y	N	Y	Y	Y	Y	N	N	N	Y	Y	Y	N	N	Y/NN/NY/NN/NN/N	Y	Y	Y	Y	Y
USGS, Branch Atlantic Mar. Geol., Woods Hole (collaborate: Puerto Rico and Wider Caribbean)	Y				Y	Y	Y	?	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y/N Y/NY/YY/Y	Y	Y	Y	Y	Y
Lab. Coast. Res., Univ. Maryland	Y	N	N	N	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	N	Y	N	Y	Y	Y	Y	Y	Y/NY/NY/NY/NY/N	Y	Y	Y	Y	Y
Dept. Mar. Sci., Univ. S. Florida	Y				Y	Y	Y	?	N	N	N	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y/NY/NY/NY/NY/N	N	N	N	N	N
Grad. School, W'ern Wash'ton Univ.					Y				N	N	N	N		Y	Y		Y		Y			Y	Y	Y/N Y/N Y/N	N	N	N	N	N
VENEZUELA					Y																								

UNITED NATIONS ENVIRONMENT PROGRAMME

CLIMATE IMPACT STUDIES IN LOW-LYING COASTAL AREAS AND SMALL ISLANDS OF UNEP'S REGIONAL SEAS PROGRAMME

Makram A. Gerges and Mahmoud Kh. El-Sayed
United Nations Environment Programme
Oceans and Coastal Areas Programme Activity Centre
Nairobi, Kenya

ABSTRACT

The threat of global climate change due to increasing concentrations of greenhouse gases has focused the attention on the global environment and the impact of human actions. One of the likely impacts of global warming is sea level rise. This phenomenon appears to be the result of the gradual increase in temperature due to the rapidly increasing levels of CO_2 in the atmosphere. This warming, in turn, could melt the ice sheets, thermally expand the oceans, and cause subsequent rises in sea level. Although the impacts of climate change are uncertain, small island states and large populations living in low-lying coastal areas will be increasingly vulnerable to the combination of sea level rise, storm surges, and coastal flooding.

In response to the anticipated global warming and sea level rise, the Oceans and Coastal Areas Programme Activity Centre (OCA/PAC) of the United Nations Environment Programme (UNEP) contributes to the activities designed to assess the potential impact of climate change, to maintain several areas covered by the Regional Seas Programme to initiate studies on the assessment of the vulnerability of coastal areas to climate change and sea level rise, as well as to assist governments in identifying and implementing suitable policy options and response measures that may mitigate the negative consequences of the expected impacts. This has been proved through the establishment of 10 regional Task Teams, and supporting seven second-generation, site-specific case studies after careful analysis of their scientific merits and evaluation of their socioeconomic importance to the region in question. These case studies comprise a more or less representative sample of various categories of coastal environments and societal conditions. To the extent possible, a common approach to the case studies is pursued in order to make the best possible use of the experiences gained in each case study and to facilitate the integration of results.

This paper aims at presenting the efforts of OCA/PAC relevant to the implications of climate change and sea level rise and to support the second-generation, site-specific case studies. In addition, it discusses the linkage between OCA/PAC and IPCC activities pertaining to the vulnerability assessment.

INTRODUCTION

Anticipated global warming as a result of the increased concentrations of greenhouse gases in the atmosphere is a pressing environmental problem to the extent that it straddles many scientific disciplines and, hence, presents major challenges. The greenhouse gases have the effect of changing the atmosphere's radiative balance by trapping more heat near the earth's surface, resulting in a possible rise in global mean surface air temperature. The Intergovernmental Panel on Climate Change reported that if the world does not act to reduce emissions of greenhouse gases, the planet will warm by about 2°C by 2030, with a rate of change of 0.2-0.4°C per decade over the next century (IPCC, 1990). This rise in temperature may appear small, but even the lower end of this range, if achieved, will cause serious changes in regional climate and will induce considerable impacts on communities and their socioeconomic well being (El-Sayed, 1991).

One of the likely impacts of global warming is sea level rise. Sea level fluctuations are, of course, part of a natural cycle. However, in recent years, scientists have noted trends that are different from the normal changes they have come to expect. Although the impact of sea level rise depends on the total net rise resulting from the vertical movements of the land and of the sea, in the last century, the eustatic sea level has risen more than 30 cm—a rate faster than that observed at any time in past millennia. This phenomenon appears to be the result of the gradual increase in temperature due to the rapidly increasing levels of CO_2 in the atmosphere; this warming, in turn, could melt the ice sheets, thermally expand the oceans, and cause subsequent rises in sea level (El-Sayed, 1991).

Although the assessment of the impacts of climate change remains uncertain, small island states and large populations living in low-lying coastal areas will be increasingly vulnerable to the combination of sea level rise, storm surges, and coastal flooding. Rapid coastal inundation is predicted for many parts of the world when, in fact, the present rate of sea level rise is about 1 to 2 mm/year. Local changes in sea level in many subsided deltaic and coastal areas for the next 50 to 60 years will be greater than the worldwide rise of sea level. By the end of the next century, it is thought that some 300 Pacific Ocean atolls will disappear beneath the sea (ASPEI, 1988). Coral islands are by far the most vulnerable to climate change. If the rate of sea level rise exceeds the rate of vertical coral growth, flooding and erosion will destroy the atolls (Tolba, 1991).

While it probably will be cost-effective for wealthy nations to protect major cities and investments against rising sea level, many developing nations are likely to find that their economies cannot support the costs of protection (Tolba, 1991). Globally, protection against a 1-meter sea level rise would cost 0.037 percent of the global gross national product (GNP)—a total of U.S. $500 billion. For Bangladesh and Egypt, however, the costs of protecting their fertile deltaic land would consume 0.1 and 0.09 percent, respectively, of their GNP—more than 25 times higher than the global average. Estimates for such nations as Brazil, The Gambia, Mozambique, and Vietnam are similarly unfavorable. The situation is even worse for small island nations. For 12 nations, all but one of them small island groups, the cost of protecting against sea level rise would involve a drain on their GNP that is 100 times greater than the global average (Delft Hydraulics Laboratory, 1990).

Therefore, the scientific evidence has made it clear that action is needed now to prepare for climate change (Tolba, 1991). From the start, the United Nations Environment Programme (UNEP) has been closely associated with research into possible climate change and responses that might reduce both the warming and the impacts. Following the First World Climate Conference in 1979, UNEP established the World Climate Impact Studies Programme, a component of the World Meteorological Organization's World Climate Programme, to carry out a variety of climate impact studies in many countries, establishing methodologies, identifying particularly vulnerable areas, and suggesting approaches for dealing with specific problems. With the World Meteorological Organization, UNEP established the IPCC in 1988, which has presented the most comprehensive report on the science of climate change, its impacts, and possible responses (Tolba, 1991).

In response to the anticipated global warming and sea level rise, the Oceans and Coastal Areas Programme Activity Centre (OCA/PAC) of UNEP launched, coordinated and financially supported a number of activities designed to assess the potential impacts of climate change and to assist governments in the identification and implementation of suitable policy options and response measures that may mitigate the negative consequences of the expected impacts. Coastal zone management is the ultimate objective of OCA/PAC activities directed toward the vulnerability assessment studies.

This paper aims at presenting the efforts of OCA/PAC to assist several areas covered by the Regional Seas Programme to initiate studies on assessing the vulnerability of their low-lying coastal areas and small islands to climate change and sea level rise. In addition, it discusses the linkage between OCA/PAC and IPCC activities pertaining to the vulnerability assessment.

Related activities for the Mediterranean and the Caribbean Seas Areas are coordinated by their respective UNEP's Regional Coordinating Units and will be presented during this workshop.

UNEP'S OCA/PAC RESPONSE TO CLIMATE IMPACTS

Since 1987, Task Teams on the Implications of Climate Change have been established for 10 regions covered by the UNEP Regional Seas Programme (Mediterranean "MED," Wider Caribbean "CAR," South Pacific "SPREP," East Asian Seas "EAS," South Asian Seas "SAS," South-East Pacific "SEP," West and Central Africa "WACAF," Eastern Africa "EAF," Kuwait Action Plan "KAP," and the Red Sea and Gulf of Aden). The initial objective was to prepare regional overviews and case studies on the possible impacts of expected climate change on the coastal and marine ecological systems, as well as on the socioeconomic structures and activities of their respective regions. In this context OCA/PAC is establishing a further Task Team for the Black Sea region later in 1992. In selecting the Task Teams, OCA/PAC considered the need for equitable geographic representation and for expertise relevant to the work of the Task Team.

The Task Teams work under the overall coordination and guidance of OCA/PAC. Some of them are cosponsored and supported by the Intergovernmental Oceanographic Commission (IOC) of Unesco.

OCA/PAC's Task Teams' long-term objectives are:

- To assess the potential impacts of climate change on the coastal and marine environment, as well as on socioeconomic activities and structures.

- To assist governments in identifying and implementing suitable policy options and response measures that may mitigate the negative consequences of the expected impacts.

The Task Teams' short-term objectives are:

- To analyze the possible impacts of expected climate change on the coastal and marine ecological systems, as well as on the socioeconomic activities and structures.
- To prepare overviews and selected case studies relevant to specific regions.

The subjects intended to be analyzed and described in the regional overviews include:

- The possible effects of the projected sea level rise on the coastal ecosystems (deltas, estuaries, wetlands, coastal plains, coral reefs, mangroves, lagoons, etc.).
- The possible effects of temperature elevations on the terrestrial and aquatic ecosystems, including the possible effects on economically important species.
- The possible effects of climatic, physiographic and ecological changes on the socioeconomic activities and structures.
- Areas or systems that appear to be most vulnerable to the expected impacts.

The regional overviews and case studies are being presented to the intergovernmental meetings convened in the framework of the relevant Regional Seas Action Plans in order to draw the countries' attention to the problems associated with expected climate change and to prompt their involvement in the development of policy options and response measures suitable for their region and countries.

On a global approach, and recognizing the lack of a comprehensive program for monitoring climate-related changes relevant to the marine and coastal environment, UNEP, IOC and the World Meteorological Organization (WMO) jointly undertook the development of a Programme for a Long-term Global Monitoring System for Coastal and Near-Shore Phenomena Related to Climate Change. It includes physical and biological parameters and provides data on global changes, with special reference to those associated with or attributed to the impacts of expected climate changes. In addition, two Task Teams were established to assess the potential impact of climate change and sea level rise on coral reefs (UNEP/IOC) and mangroves (UNEP/UNESCO).

CRITERIA AND APPROACH FOR IMPLEMENTING CASE STUDIES

After completing the initial overviews and impact studies, the Task Teams recommend site-specific case studies on the vulnerability assessment of climate change and sea level rise in their respective regions. The site-specific case studies will be presented at national seminars in the concerned countries. The national authorities likely to implement the case studies will be invited to the seminars to review and discuss the case studies and to recommend appropriate policy options. Once completed, these studies will assist governments and national authorities in defining and implementing specific policy options and suitable response measures.

OCA/PAC has adopted the provisional findings and recommendations of the IPCC (1991) as a starting point in conducting the second-generation, site-specific case studies. Each case study supported by OCA/PAC will produce a report based on the Common Methodology for assessing vulnerability to sea level rise. Each case study report should identify the assistance that would be needed to implement integrated coastal zone management planning programs to address vulnerability to accelerated sea level rise and other coastal impacts.

Therefore, OCA/PAC has provided the regional Task Teams with guidelines to be followed, as closely, while submitting their case study proposals (Table 1). This aimed at facilitating the screening and in-depth analysis of the submitted case studies for their selection and financial support from UNEP. Consequently, nine case studies were submitted for consideration and financial support by UNEP.

TABLE 1. GUIDELINES FOR PREPARING SITE-SPECIFIC CASE STUDIES

Project Title(s)

1. Objectives:

2. Inventory of study area characteristics :
   Geographic location
   Physical (coast type, water level, river discharges, nature and extent of coastal protection facilities, etc.)
   Habitats and species
   Socioeconomic information (GDP, population, etc.)
   Land use and value

3. Assumptions (Boundary conditions):
   Second World Climate Conference (Geneva, 1990)
   IPCC, July 1991
4. Outputs:

5. Work plan:
   Duration of the project
   Time-table
   Personnel required

6. Institutional framework and logistics:

7. Estimated budget:

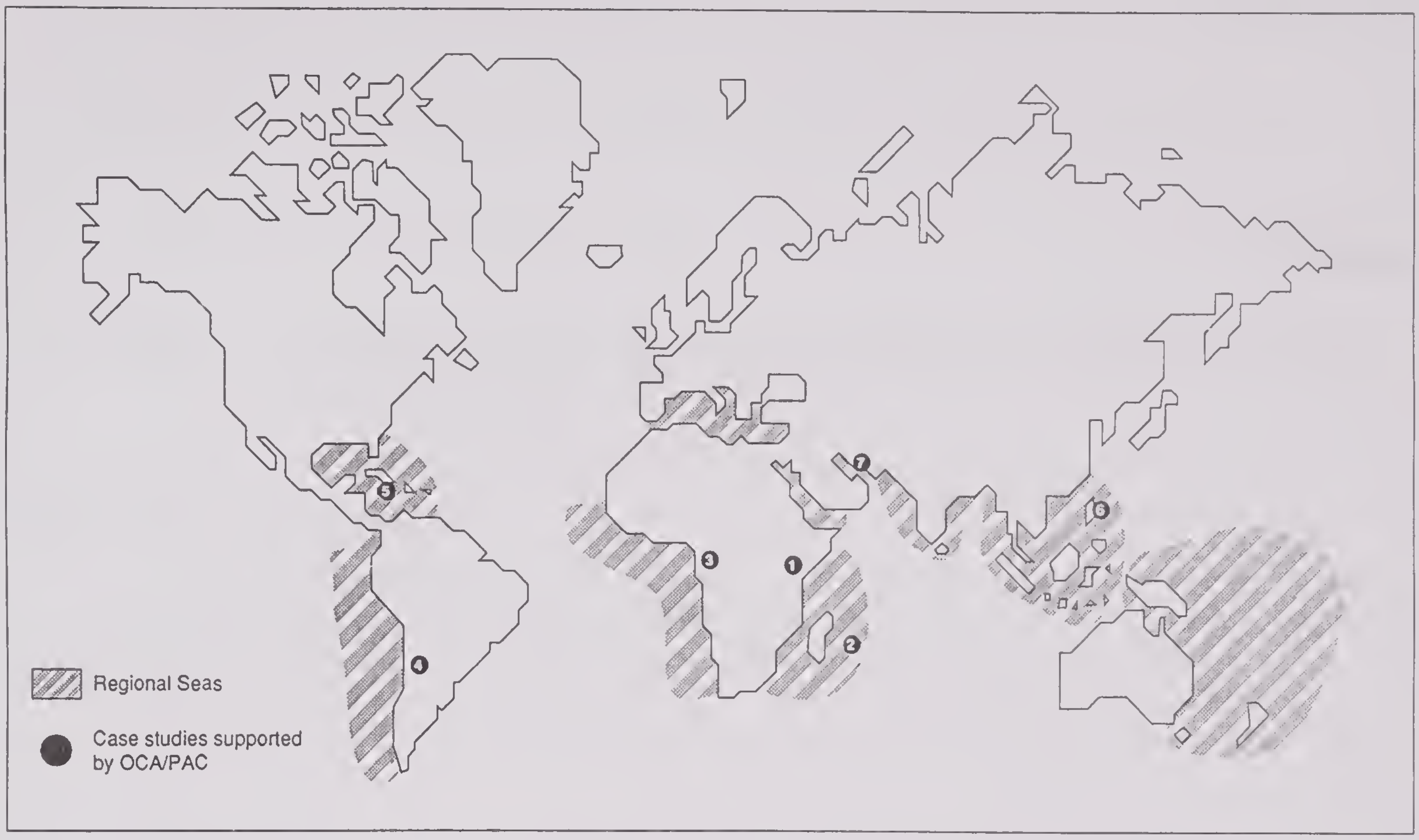
It is worth mentioning that related activities for implementing case studies for some Regional Seas Areas (e.g, Mediterranean, Caribbean, South Asia, and South Pacific) are largely coordinated by their respective Regional Coordinating Units. Some of these studies will be presented separately during this workshop.

After careful analysis of the scientific merits of each proposal and evaluation of its socioeconomic importance to the region in question, UNEP decided to support seven case studies in low-lying coastal areas and small islands, selected from among the proposals submitted for consideration (Figure 1; Table 2). These case studies comprise a more or less representative sample of various categories of coastal environments and societal conditions. To the extent possible, a common approach to the case studies is pursued in order to make the best possible use of the experiences gained in each case study and to facilitate the integration of results. The objectives of the case studies proposed by IPCC were adopted by all Task Teams. However, specific objectives for each case study were suggested from their respective Task Teams.

TABLE 2. SITE-SPECIFIC CASE STUDIES SUPPORTED BY OCA/PAC

Title	Area(s)	Specific Objectives	Outputs	Institutional Framework	Status
(1) EAF: Implications of climate change on the EAF low-lying coastal areas	•Mombasa •Malindi-Watamu •Tana River Delta	•Socioeconomic •Define vulnerable areas •Policy response	•Data base •CZM Management	UNEP-National Com.Int. Geosphere Bios.Prog. (in association with Nairobi University)	Partial Study Sites (Coast, Mangrove, Delta) Started Jan. '92 Ending Dec. '92
(2) EAF: Vulnerability assess. of selected coasts of Mauritius in the context of climate change and SLR	•Port Louis •Pomponetta	•Socioeconomic •Define vulnerable areas •Policy options	•Vulnerability Assess. •Models - cartography •Impacts study •Mitigation	UNEP-Ministry of Environment & Quality of Life (Dept. of Environment)	Partial Study Sites (Coast, Corals) Started Jan. '92 Ending Dec. '92
(3) WACAF: Implications of climate changes and SLR on the Niger Delta, Nigeria	Niger Delta	•Socioeconomic •SLR impacts on delta •Define most vulnerable areas	•Data base •Strategies for mitigation •Workshop	UNEP - NIOMR	Partial Study Sites (Delta) Started Jan. '92 Ending Dec. '92
(4) SEP: Socioeconomic implications of expected climate change in SEP	SEP	•Socioeconomic implications •Define vulnerable areas •SLR impacts on ecosystem	•Data base CZM •Thematic maps •Impacts study •Mitigation	UNEP - CPPS	Regional Study Sites Started Jan. '92 Ending Dec. '92
(5) CAR: Vulnerability assessment in the CAR: a case study	Theoretical small island	•One-point numerical socio-economic model •Develop operational procedure V.A.	•Develop methodology •Develop policy •Workshop	UNEP - RCU/CIMAS	Regional Study Sites Started Jan. '92 Ending Dec. '92
(6) EAS: Impact of SLR on the reclaimed land of Singapore	Reclaimed land	•Using 0.3–1 meter SLR scenarios on reclaimed land	•Report of maps •Possible strategy	UNEP-National University of Singapore	Partial Study Sites (Reclaimed land) Started Jan. '92 Ending Aug. '92
(7) KAP:Effect of climate change and SLR on the mangrove Avicennia marina ecosystem in Qatar	Eastern coast of the Qatari Peninsula	•Assess impacts on mangrove ecosystem •Socioeconomic	•Data base	UNEP-SARC	Partial Study Sites (Mangrove) Started Mar. '92 Ending Dec. '92

FIGURE 1. MAP SHOWING CASE STUDIES SUPPORTED BY OCA/PAC



KENYA

The title of this case study is "Implications of Climate Change on the Eastern African Low-Lying Coastal Areas and Small Islands: Proposal for the Kenya Case Study." The case study's objectives are:

- To examine the possible effects of climate change on the socioeconomic structure and human-use system.

- To determine the areas or systems most vulnerable to climate change.

- To identify and propose suitable management and policy response options.

The major features of the Kenyan coast include a narrow fossil coral reef broadened inland by a narrow strip of coastal sands. Most of the coral reefs are raised only few meters above mean sea level. Other common features of the Kenyan coast are the mangrove swamps.

Due to the large variations in land-use activities and in the geomorphology of the Kenyan coastal region, three sites have been selected for this study:

- Mombasa Island and the surrounding areas.
- The Malindi-Watamu Biosphere reserve.
- The Tana River delta.

The outputs of the study are expected to be:

- A comprehensive and useful data base for managing the selected study sites.
- A proposal of management and environmental policy that would enhance the decision-making processes on coastal and marine resources.

MAURITIUS

The title of this case study is "Vulnerability Assessment of Selected Coastlines of Mauritius in the Context of Climate Change and Sea Level Rise. The study's objectives are:

- To examine the possible impacts of climatic change on coastal human activities and socioeconomic structures.
- To determine areas or systems that appear most vulnerable to climate change.
- To identify and recommend appropriate policy options and strategies to mitigate the likely negative impacts.

The study area consists of:

- Port-Louis—The main features of the urban and harbor areas of Port-Louis are:
    - Low-lying coastline enclosed by Port-Louis mountain range.
    - A bird sanctuary in the Ruisseau Terre Rouge estuary.
    - Harbor-water draught of 5 meters.
    - Two sewage outfalls.
    - Seasonal flooding/siltation in case of heavy rain and rapid runoff.
    - Landslide at La Butte.
    - A densely populated area/commercial center.
    - Reef does not exist around the harbor.
    - Fishing port at Trou Fanfaron.
- The Pomponnette area—This area is located on the south coast of the island. It is exposed to the full force of the prevailing southeast trade winds. This area is skirted by coral reef formation.

The expected output of this case study is a vulnerability assessment of two different types of coast on a tropical high island using historical data, ground-truth, and fieldwork aimed at building models and related cartographic representations to outline the implications on coastal areas and socioeconomic activities.

NIGER DELTA (WACAF)

The title of this case study is "Implications of Climatic Changes and Sea Level Rise on the Niger Delta, Nigeria." The study's objectives are:

- To outline the possible effects of sea level rise on the Niger Delta.
- To examine the impacts on the socioeconomic structures and activities.
- To identify the areas most vulnerable to sea level rise.

The Niger Delta covers an area of about 16,340 km^2. This area is of great economic importance because it houses Nigeria's main source of oil and gases. Its extensive mangroves also serve as spawning grounds for a variety of fisheries resources. Fishing settlements and terminals, oil wells, and storage tanks are prominent features of the entire coastline.

The expected outputs of this case study are:

- A report on the implications of climate change and sea level rise on the coastal and marine environment of the Niger Delta.
- Recommendations on strategies for mitigating the expected impacts on the Niger Delta and, as a follow-up action, convening a workshop to bring information to the government and/or the public.

SOUTH-EAST PACIFIC (SEP)

The title of this case study is "Socioeconomic Implications of Expected Climate Change in the South-East Pacific Region." The study's objectives are:

- To examine the possible effects of sea level rise on coastal ecosystems (deltas, coral reefs, mangroves, etc.).
- To examine the implications on the socioeconomic structures and activities.
- To identify the areas most vulnerable to climate change.
- To propose suitable management measures and policy response options.

The coastal zone of the South-East Pacific region is approximately 10,527 km long. It varies in width and encompasses in many places coral reefs and mangroves. This latitudinal range gives the region a broad climatic and geomorphologic characteristics, that make it rather complex. El Niño manifests itself in the region in different climatic, ecological, and geological events. The socioeconomic effects of El Niño have been disastrous.

The expected outputs of this case study are:

- A data base to be used for coastal zone management.
- Thematic maps of components (or groups of components) of the natural and socioeconomic environment.
- An evaluation of impacts on selected areas.
- Mitigation measures and response options.

WIDER CARIBBEAN (CAR)

The title of this case study is "Vulnerability Assessment in the Wider Caribbean Region: A Case Study." The study's objectives is to develop an operational procedure to provide a consistent, quantitative description of a nation's vulnerability to sea level rise. This will be accomplished by first developing a "one-point" numerical socioeconomic model on a purely *theoretical small island* that has most of the physical characteristics of the region. This island will be modeled as one point, and the model will be of a dynamic kind and will include socioeconomic, physical, ecological, and climatological variables. The model will be then customized to a specific "case-study" island of similar character, evaluated, refined, and then used as a basis for training for management objectives.

A small island will be determined as part of the first year's efforts. This island it will be typically Caribbean in characteristics (beaches, corals, mangroves, river with a delta, etc.). For socioeconomic approaches, the island will be typical artisanal fisheries with its infrastructure.

The expected outputs of this case study are:

- A methodology for assessing the impacts of sea level rise.
- A policy support system.
- Course material for a workshop or a "training for trainers" program.
- Execution of at least one case study to test the robustness of the methodology, etc.

SINGAPORE (EAS)

The title of this case study is "Impact of Sea Level Rise on the Reclaimed Land of Singapore." The study's objectives are:

- To assess (mapping) the impact of sea level rise, (0.3–1.0 meter), on the reclaimed land of Singapore.

- To define future strategies and measures to protect and use these lands.

The study area consists of reclaimed land in Singapore. The expected output of the study is a report, including maps showing the different impacts with different sea level rise scenarios and an evaluation of the possible strategies and measures to be undertaken.

QATAR (KAP)

The title of this case study is "Effect of Climate Change and Sea Level Rise on the Mangrove *Avicennia Marina* Ecosystem in Qatar." The study's objectives are:

- To assess the environmental and climatological changes and their impacts on the mangrove ecosystem.

- To determine the effects of temperature rise and sea level rise on the ecophysiology and the dynamics of the involved species populations.

The study area consists of the eastern coast of the Qatari Peninsula. The expected output is a data base that will contain the information from this study and basic information. The final results will be socioeconomically tested.

IMPLEMENTATION OF CASE STUDIES

The selected case studies will be conducted by their respective groups of scientists (national or regional). OCA/PAC provided these groups with guidelines for vulnerability assessment and for the outlines of the case studies' report (Tables 3 and 4). These guidelines were based on the findings and recommendations of IPCC. In addition, the following principles were agreed to for the preparatory phase of these case studies:

- The case study will last 9–12 months because of the limited accessibility of existing knowledge and readily available data in the given selected area, and will be limited to the geographic area indicated in the original project proposal. As such, it can only be considered as a sample of the process required to assess vulnerability, to identify response strategies, and to develop management plans.

- Depending on the results of the above case study, further development of the study could be considered as a second phase either under UNEP's (OCA/PAC) climate change program, possibly in association with the IPCC or, if relevant, as an integrated part of the joint UNEP/IOC program of the Long-Term Global Monitoring System of Coastal and Near-Shore Phenomena Related to Climate Change.

- The study will be conducted according to the project proposal on the site-specific case studies on vulnerability assessment of low-lying coastal areas and small islands to climate change and sea level rise, submitted to UNEP from the respective implementing institution.

- The case study has to be conducted as closely as possible to the common methodology for assessing the vulnerability of coastal areas to sea level rise.

TABLE 3. STEPWISE APPROACH FOR VULNERABILITY ASSESSMENT

Step 1	Delineate coastal region case study area.
Step 2	Specify scenarios for sea level rise.
Step 3	Specify direct physical effects.
Step 4	Conduct an inventory of the natural system characteristics and responses to SLR.
Step 5	Conduct an inventory of the socioeconomic system characteristics, and identify the exposure of the socioeconomic system to SLR and natural system responses.
Step 6	Formulate response strategies, and estimate corresponding costs, resulting effects, and remaining damages.
Step 7	Conduct a vulnerability assessment of the case study area.

The study should result in a comprehensive report. In addition to the above, the report should identify any further requirements to implement an integrated coastal management program to address vulnerability to sea level rise and other coastal impacts. Also, the expected outputs and objectives as per the original proposal have to be fulfilled.

TABLE 4. OUTLINE OF A CASE STUDY REPORT

1. Summary
   Introduction/Methodology and Analysis Conditions/Principal Findings

2. Specification of sea level rise scenarios

3. Description of the impact area
   Boundaries of case study area/Characteristics of natural system/
   Characteristics of socioeconomic system/Institutional arrangements

4. Identification of impacts of sea level rise
   Impacts on natural system/Impacts on socioeconomic system

5. Identification of nonclimate change factors affecting coastal resources and uses

   a. Natural: coastal erosion, subsidence
   b. Human: coastal development, sand and coral mining, aquifer, oil/gas extraction

6. Identification of response strategies
   Retreat/Accommodation/Protection/Impacts on natural system and remaining damages

7. Vulnerability assessments
   Vulnerability Assessment: natural system/socioeconomic system/national context

8. Sensitivity analysis
   Development plans and socioeconomic trends/Other climate change conditions

9. Recommendations

   a. Analysis of remaining impact areas and aspects not covered
   b. Priority setting on vulnerable areas and economic sectors
   c. Comments on existing development plans
   d. CZM (coastal zone management) planning capabilities and institutional arrangements
   e. Requirements to develop additional capabilities

Figure 2 summarizes the stepwise approach for implementing OCA/PAC's case studies. Table 5 compares the IPCC and OCA/PAC approaches for implementing case studies.

FIGURE 2. STEPWISE APPROACH FOR THE IMPLEMENTATION OF OCA/PAC'S CASE STUDIES

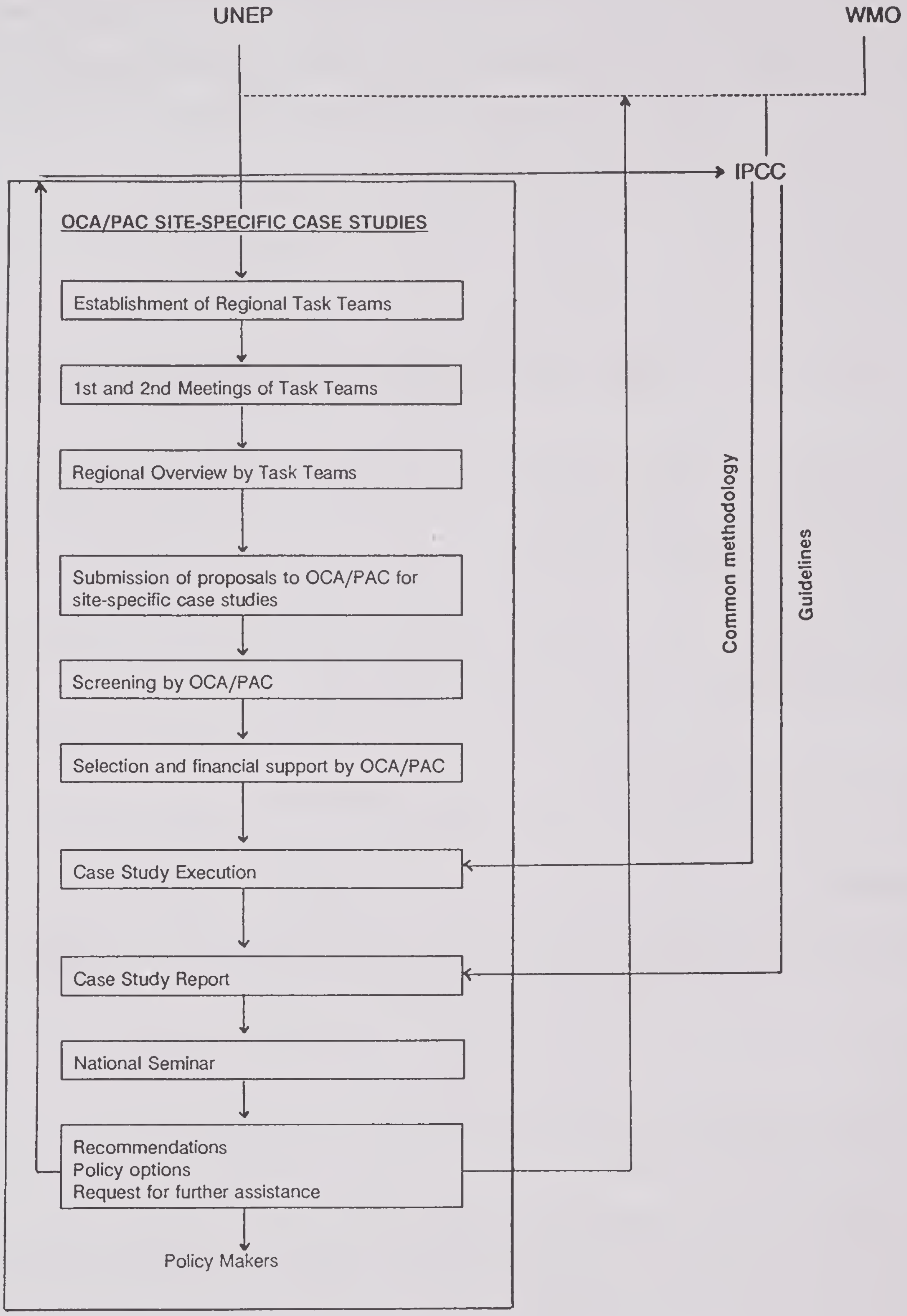

UNEP
WMO
IPCC
OCA/PAC SITE-SPECIFIC CASE STUDIES
Establishment of Regional Task Teams
1st and 2nd Meetings of Task Teams
Regional Overview by Task Teams
Submission of proposals to OCA/PAC for site-specific case studies
Screening by OCA/PAC
Selection and financial support by OCA/PAC
Case Study Execution
Case Study Report
National Seminar
Recommendations
Policy options
Request for further assistance
Policy Makers
Common methodology
Guidelines

TABLE 5. IPCC-OCA/PAC ANALOGOUS STEPWISE APPROACH TOWARD THE VA STUDIES

VA Studies Criteria and Strategy for implementation	IPCC	OCA/PAC (Regional and Global)
(1) Objectives of case studies:		
• To assess the vulnerability profile of specific regions or countries		
• To identify priority assistance needs of specific regions or countries		
• To provide a basis for a more global assessment of the vulnerability of coastal regions and common approach to deal with the problems		
(2) Execution of VA case studies:		
• Case studies should be based on existing knowledge and readily available data		In some regions or countries, even basic data are not available
• Total duration of case study execution		
• Methodology: Common, replicable		
• Flexibility of approach	4-6 months	9-12 months (see above item)
(3) National seminars	-	
(4) Case studies reports		
(5) Involvement of the national end users (policy-makers) in the formulation of the work program and the study outline		

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IMPLICATIONS OF EXPECTED CLIMATE CHANGE IN THE MEDITERRANEAN REGION

L. Jeftic
Mediterranean Coordinating Unit
United Nations Environment Programme
Athens, Greece

THE MEDITERRANEAN STUDY: PHASE I (1987–89)

The environmental problems associated with the potential impacts of expected climate change may prove to be among the major environmental problems facing the marine environment and adjacent coastal areas in the near future. Therefore, in line with the Decision of the Fourteenth Session of the United Nations Environment Programme (UNEP) Governing Council on Global Climate Change, the Oceans and Coastal Areas Programme Activity Centre (OCA/PAC) of UNEP, in cooperation with several intergovernmental and nongovernmental organizations, launched, coordinated, and financially supported a number of activities designed to contribute to an assessment of the potential impacts of climate change and to assist the governments in identifying and implementing suitable response measures that may mitigate the negative consequences of the impacts.

As part of these efforts, Task Teams on Implications of Climate Change were established in 1987 for six regions covered by the UNEP Regional Seas Programme (Mediterranean, Wider Caribbean, South Pacific, East Asian Seas, South Asian Seas, and South-East Pacific), with the initial objective of preparing regional overviews and site-specific case studies on the possible impacts of expected climate change on the coastal and marine ecological systems, as well as on the socioeconomic structures and activities of their respective regions. Three additional Task Teams were established, two in 1989 (for the West and Central African region and for the Eastern African region) and one in 1990 for the Kuwait Action Plan region).

The overviews and case studies were expected:

- To examine the possible effects of sea level changes on the region's coastal ecosystems (deltas, estuaries, wetlands, coastal plains, coral reefs, mangroves, lagoons, etc.).
- To examine the possible effects of temperature elevations on the region's terrestrial and aquatic ecosystems, including the possible effects on economically important species.
- To examine the possible effects of climatic, physiographic, and ecological changes on the region's socioeconomic structures and activities.
- To determine areas or systems that appear to be most vulnerable to the above changes.

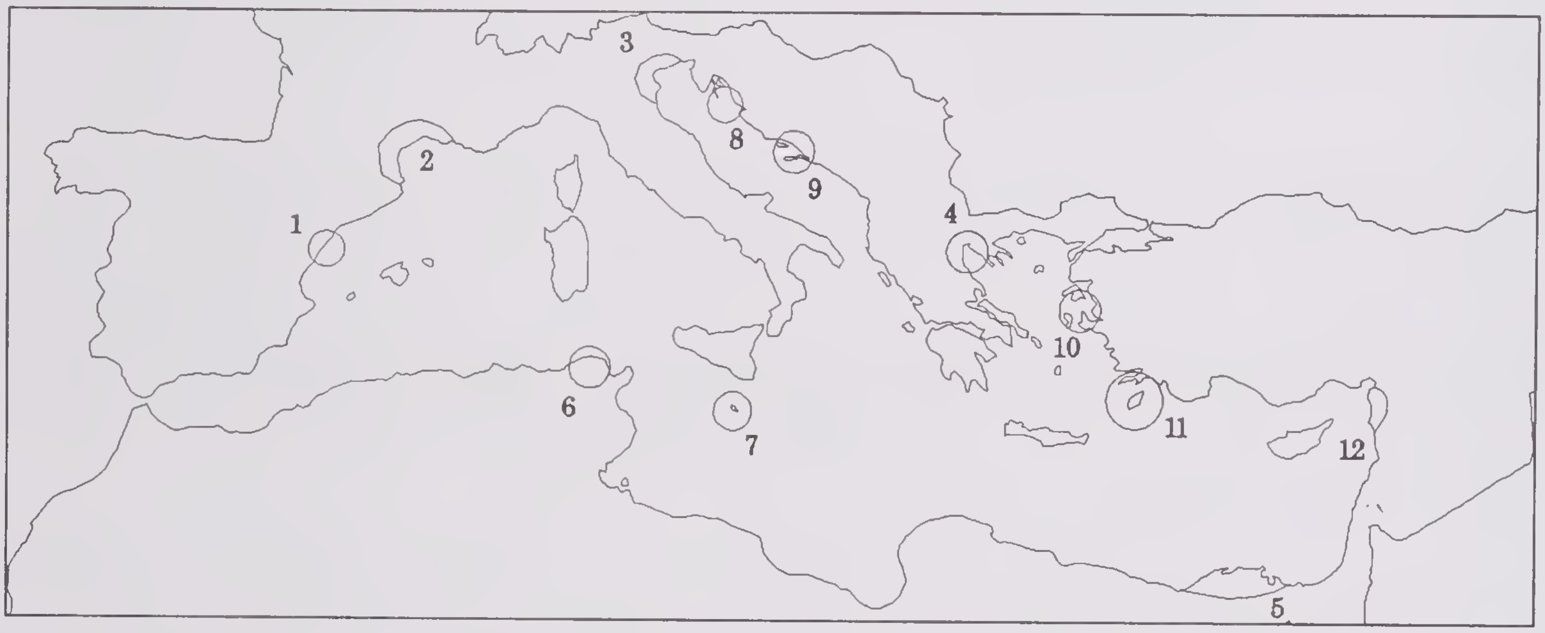
The regional studies were intended to cover the marine environment and adjacent coastal areas influenced by or influencing the marine environment and were planned to be presented to the intergovernmental meetings convened in the framework of the relevant Regional Seas Action

Plans in order to draw the countries' attention to the problems associated with expected climate change and to prompt their involvement in development of policy options and response measures suitable for their region. The site-specific case studies developed by the Task Teams were planned to be presented to national seminars. Once the initial objective of the Task Teams (impact studies) was achieved, they were meant to concentrate on providing assistance to national authorities in defining specific policy options and suitable response measures.

The Task Team on Implications of Climate Change in the Mediterranean region was established in mid-1987 with the aim of preparing a Mediterranean regional overview of the implications of climate change for coastal, terrestrial, and aquatic ecosystems, as well as for socioeconomic structures and activities. The aim of the Task Team was to use all relevant information available and to identify the geographical areas that appear to be most vulnerable to climate change.

The Task Team met twice in 1987 and identified eight topics for regional impact assessments (climate change, sea level change, oceanography, coastal lowlands, hydrology, land degradation, vegetation, and socioeconomic activities) and six site-specific case studies (deltas of the rivers Ebro, Rhone, Po, and Nile, Thermaikos Gulf, and Bizerte/Ichkeul Lakes) (Figure 1). Also, the Task Team identified the names of potential authors of assessment and case studies and agreed that a bibliography of papers dealing with climate change and its implications should be prepared.

FIGURE 1. LOCATIONS OF CASE STUDIES IN THE MEDITERRANEAN REGION



1987-1989

1. EBRO DELTA
2. GULF OF LION/RHODE DELTA
3. PO DELTA/VENICE LAGOON
4. THERMAIKOS GULF
5. NILE DELTA
6. LAKES ICHKEUL/BIZERTE

1990-1992

7. MALTA ISLAND
8. CRES/LOSINJ ISLANDS
9. KASTELA BAY
10. IZMIR BAY
11. RHODES ISLAND
12. SYRIAN COAST

In 1989, the Mediterranean Task Team presented the results of the assessment and case studies at the Joint Meeting of the Task Team on Implications of Climatic Changes in the Mediterranean and the Coordinators of the Task Teams for the Caribbean, South-East Pacific, South Pacific, East Asian Seas, and South Asian Seas regions, at which 17 papers concerning the Mediterranean were presented (UNEP, 1988).

On the basis of the papers presented and other available information, an overview of the implications of expected climate change in the Mediterranean region was prepared and published (Sestini et al., 1989). A popular booklet, *High and Dry, Mediterranean Climate in the Twenty-first Century* , was also published (UNEP, 1989b). A bibliography on the effects of climate change and related topics, including about 1,500 references, was prepared and published by the Mediterranean Coordinating Unit of UNEP (UNEP, 1989a). A book on the implications of climate change in the Mediterranean, including the results of eight topical regional impact assessments and six site-specific case studies is in press (Edward Arnold Publishers).

This paper summarizes the results of the first phase (1987–89) of the work of the Mediterranean Task Team.

THE MEDITERRANEAN REGION

The Mediterranean Sea lies between Europe, Asia, and Africa. It extends about 4,000 km from Gibraltar to Syria. Excluding the Black Sea, it covers about 2.5 million km^2, with an average depth of about 1,500 meters, a maximum depth of 5,000 meters, and a volume of 3.7 million km^3 (Figure 1). The Mediterranean coastline is about 46,000 km long, of which 19,000 km is the coastline of the Mediterranean islands. The Mediterranean Sea is bordered by 18 countries; the coastlines of individual countries range from 15,000 km (Greece) to 5 km (Monaco). Although few in number, major Mediterranean rivers (Ebro, Rhone, Po, Vardar, Ceyhan, and Nile) inject large volumes of sediment into the system. On the other hand, much of the coast is drained by short mountainous rivers that individually drain small areas on a highly seasonal basis. Collectively these may transport more sediment to the basin, but certainly less water.

Climatically, the Mediterranean is transitional and characterized by its winter-dominated rainfall, dry summers, and profusion of microclimates due to the alternating mountains and inland seas. There is a temperate, damp climate in the north and a hot, arid climate in the south. Rainfall decreases from west to east and from north to south, varying from more than 1,500 mm yr^{-1} (Alps, Pyrenees, and western part of Yugoslavia) to less than 100 mm/yr. The summer drought lasts four months on the average, with sometimes—though rarely—a little rain in June along the European coasts. In the warmest months, evaporation is usually higher than in the adjoining desert areas to the south and east; in winter, it is less than half the summer figure. Characterized by very weak tides, the Mediterranean is often considered a tideless sea.

The Mediterranean Sea has a deficient hydrological balance, with loss through evaporation exceeding the input of water through runoff and precipitation. This deficiency is mainly compensated by the influx of Atlantic surface waters through the Strait of Gibraltar. An overwhelming problem is the striking disparity of water potential between the northern and southern shores of the Mediterranean. In view of the rapid increase in water requirements and the relative poverty of some of the coastal countries, international transfers no longer should be regarded as utopian schemes. The river runoff in the Mediterranean is estimated at about 15,000 m^{3}s^{-1} of which 92 percent flows from the northern shore and the rest if from draining from the southern shore. Biological productivity in the Mediterranean Sea is among the lowest in the world, because of the low nutrient content of the surface waters.

Over the centuries there has been an increasingly serious interference with natural balances throughout the Mediterranean basin. This has altered the original aspects of the countryside and has brought about, through a constant process of deterioration, extremely precarious situations requiring urgent and appropriate remedies. Deltaic and lowland coasts are at present experiencing serious environmental problems, due not to recent climate oscillations, but to careless development of land use over the last 50 years. These include the urbanization of the coast, the building of deep harbors and coastal defense structures, a decrease of lagoon surface (via land reclamation), enhanced land subsidence caused by water extraction, the deterioration of river waters and solid discharges, pollution of coastal waters, and salinization of ground waters. Other basin-wide problems include forest degradation and fires, soil erosion, and desertification.

Desertification is increasing in the Mediterranean arid zone at the alarming rate of several hundred thousand hectares per year. It is generally agreed that desertification results from two main factors: aridity (periodical prolonged droughts) and destructive land-use practices. In the Mediterranean arid zone, the population has increased almost five-fold since the beginning of the century; in all likelihood, it will double again by the year 2000. The consequences of this population explosion include increased cultivation and clearing of steppe, increased numbers of livestock, overgrazing, destruction of forests and woody vegetation in general, salinization of large areas as a result of faulty irrigation projects, inadequate human settlements, and emigration. In addition, probably 30,000–40,000 hectares are lost annually in the Mediterranean arid zone by salinization or alkalinization.

Coastal regions in the Mediterranean cover an area of 1,280,802 km^2, or 15 percent of the total area (8,528,787 km^2) of the 18 countries that border the basin. These countries in 1985 had a total population of 350 million, of which 37 percent live directly in the coastal area (Grenon and Batisse, 1989). The population density is greatest in coastal regions, ranging from 250 inhabitants per km^2 to up to 1,000 per km^2 in the Nile delta. According to one average projection, the population in the Mediterranean can be expected to reach 433 million in the year 2000 and 547 million in 2025 (Grenon and Batisse, 1989). This phenomenon will lead to a shift in the center of concentration of the Mediterranean population from the northwest (Spain, France, Italy) to the eastern and southern parts of the Mediterranean (Egypt, Turkey, Algeria). Post-World War II development of the Mediterranean region has been extremely pronounced, accompanied by intensified industrialization and the development of tourism. This has accelerated the urbanization of the coastal areas and immediate hinterland—i.e., Alexandria, Algiers, Athens, Barcelona, Beirut, Genoa, Izmir, Marseille, Naples, Rome, and Tunis. Of the total population of the Mediterranean coastal regions in 1980, 57 percent was urban, with a projected figure of 75 percent by 2025. In the countries of the southern Mediterranean, almost the entire increase in urban population will take place in the cities in the coastal regions (Grenon and Batisse, 1989).

The role of coastal regions as focal points of development and construction is particularly pronounced in the southern countries, where all the efforts in the development of the interior have encountered great difficulties, with the exception of Morocco. Although the centers of development in the European Mediterranean countries often lie outside the coastal belt of the Mediterranean, even in these countries we find an increasing degree of littoralization. The development and construction in the coastal regions take place themselves mainly in the vicinity of cities and ports, with much of the remaining coast being used for tourism.

The wide variation in natural political and economic systems (both past and present) within the region, as well as the variation in its disposable resources, have resulted in great differences in the level of development of Mediterranean countries. Compared to the developing countries in the eastern and southern regions of the Mediterranean (except Israel), the highly developed industrial countries in the northwest (France, Italy, Spain) and countries with rapidly developing industrialization processes (Greece, Yugoslavia, Turkey) represent the global north-south economic contrast. The state of development of the Mediterranean countries is illustrated by marked contrast in gross domestic product per capita (GDPC) (Grenon and Batisse, 1989), from U.S. $670 (Morocco) to U.S. $7,720 (France) (in 1985). GDPCs greater than $3,000 have been recorded in France, Italy, Israel, and Spain,while most other countries have recorded values of between U.S. $800 and $1,600. As a result of a major production of oil, Libya's GDPC of U.S. $3,917 represents an exception, but other indicators clearly show that it belongs to the group of developing countries.

Ancient traditions have resulted in a common, though multifaceted Mediterranean agriculture. Characteristic products are olive oil, wine, citrus fruits, hard grain, and sheep. Agricultural production activities include agriculture by irrigation, rain-fed agriculture, livestock production, grazing land management, and forestry. The coastal regions in the Mediterranean have relatively little agricultural land, that is of high quality. However, Mediterranean agriculture, particularly in the drier parts of the area, is characterized by an extensive misuse and overexploitation of the natural resources, which are (1) limited, due to overall lack of good soil and water supplies, and (2) prone to degradation due to irregular rainfall and a hostile climate toward soils that are often on slopes and fragile. Periodic fires, recurrent wind storms and torrential rains destroy the woody and herbaceous vegetation.

Farmland represents some 36 percent of the overall area; forest and shrubland, 29 percent; rangeland, 22 percent; and wasteland and nonagricultural areas, 13 percent. In Mediterranean Europe land use is fairly uniform, since forestation varies from 20 percent (Greece) to 40 percent (Portugal) (average 29 percent). The trend is toward an increasing farmland and range land abandonment in marginal areas, compensated by sharp increases in reforestation and urbanization. The opposite trend is witnessed in the south and east, where forest and shrubland decrease and cropland expands, especially land devoted to cereal cultivation. The actual surface cultivated in cereals is probably about 3.5 times what it used to be in the 1950's. Probably some 50 percent of the arid steppes range ands in the 100–300 mm isohytes have been cleared over the past 30 years and are today more or less regularly cropped (barley and wheat) under subsistence farming conditions with very low average yields (100–300 kg/ha/yr). The ever-growing clearing of arid steppes range land is the major cause of desertification in North Africa and the Near East. Given the trends of the past 40 years, in the near future virtually all land soft enough to be tilled will be cultivated for cereals, even though the risk involved will be high and the yields low. In spite of the increase in cultivated area, the annual production of cereals per inhabitant decreased from 260 kg in 1980 to 195 kg in 1985. Cereal yields have increased six times faster in the northern Mediterranean countries; but population has increased four times quicker in the south (3.2 versus 0.8 percent per year). The gap in food production per capita between north and south therefore is increasing rapidly. The gap between local supply and demand grows nearly as fast as the demographic expansion of the human population (Jeftic et al., 1989).

The Mediterranean is one of the regions of the world where the social and economic importance of fishing is considerable. Prior to 1940, the annual fishing yield in the Mediterranean and the Black Sea was less than 500,000 tons. By 1974 it had reached 1,300,000 tons, of which 750,000 came from the Mediterranean. These catches, however, represent only a very small portion (little more than 1.8 percent) of the annual worldwide catch. The region's output of fish is clearly not sufficient to meet the demand, which in 1985 reached 5.5 million tons. At present, time two-thirds of the fish consumed come from outside the area, mainly from the Atlantic. The Mediterranean possesses a considerable potential for aquaculture in coastal waters. There is a long tradition of breeding fish and shellfish, a favorable climate, large tracts of water that could be used, and a large market. Under these conditions, aquaculture in the long term could produce several hundred thousand tons of fish and shellfish.

The Mediterranean region is the greatest tourist destination region in the world, and tourism is the greatest "consumer" of the Mediterranean coast. For example, tourist developments cover 42 percent of the Spanish mainland and islands coasts. The total number of international and domestic tourists in the Mediterranean countries in 1984 amounted to some 213 million, and some 45–50 percent of this number stayed in or visited the coastal regions of these countries. Tourists occupy 5,082,000 hotel beds and 28,223,000 beds in other forms of accommodation.

Tourist facilities take up 2,187,890,000 m^2 of space on the coast. Water consumption in 1984 amounted to 569 million m^3 (Jeftic et al., 1989). According to all estimates the number of tourists in the Mediterranean coastal region in the year 2000 could reach 120–180 million; by the year 2025, this could reach 170–340 million (Grenon and Batisse, 1989).

Out of the total 2,155 trading ports in the world, 183 lie on the Mediterranean. However, only 18 of these ports account for some 90 percent of the total maritime transport of goods. Some 15 percent of the total world petroleum traffic passes through the Mediterranean (Jeftic et al., 1989). Urban, industrial, and tourist development has taken up an enormous percentage of the coast. Railway and road communications are often built in the immediate vicinity of the coast. Coastline use in some regions amounts to as much as 90 percent (the French Riviera, the regions around Alexandria, Athens, Barcelona, Istanbul, Marseille, Naples). In Catalonia 387 out of 580 kilometers of shoreline have been used for urban, port, industrial, and tourist development. Urban and tourist occupation amounts to some 20 percent in Yugoslavia and 75 percent along the Romagna coast (Italy) (Jeftic et al., 1989).

The existing development trends could lead to a situation whereby the Mediterranean countries by 2025 will have a consumption of 1 billion tons of petroleum equivalents (compared to the present 500 million tons), and 150 million cars (in contrast to the present 50 million). Most likely, 95 percent of the coast will be urbanized, and the number of tourists will increase significantly (Grenon and Batisse, 1989). The increase in the population, particularly its shift from the northwest to the south and east, will lead to increased energy needs, particularly electric energy, necessitating 150–200 power stations. In view of the need for vast quantities of water for cooling these thermal power stations, most (particularly in the south) will be built in the coastal region. The need for creating new jobs will require heavy industrialization, which, in the southern regions of the Mediterranean, will be concentrated in the coastal areas.

IMPACTS OF CLIMATE CHANGE ON THE MEDITERRANEAN COASTAL ENVIRONMENT

IMPACTS ON MARINE PARAMETERS

To understand the Mediterranean response to predicted climate change it is necessary to understand both forcing functions and responses over the entire subtidal frequency range. The forcing variable at shorter time scales, like atmospheric pressure and wind variations, will be influenced by changes in climate. The likely northward shift of the atmospheric circulation pattern will influence the path and frequency of passage of mid-latitude cyclones over some of the Mediterranean area, and various marine parameters will also be affected (Gacic et al., 1988).

The horizontal density gradient set up by evaporation is an important source of large-scale wintertime circulation. However, transients in the residual circulation are also strongly affected by local winds. Therefore, any appreciable change in the seasonal distribution of the wind frequency will result in changes of the volume of the formed deep water as well as in changes of the circulation pattern of parts of the Mediterranean (e.g., northern Adriatic). The wind not only affects the sea level changes but also is very important in generating the vertical convection and deep-water formation processes. The sea level slope between connected basins, which dictates water exchange between them, is not due exclusively to differences in the atmospheric pressure between the two areas. Therefore, studies of the sea level response to the atmospheric forcing are important from the viewpoint of the barotropic water exchange between connected basins.

The impact of large-scale climate variations on the order of a few years probably will not be restricted to the observed salinity and sea level changes, but will also influence other parameters, such as horizontal density gradients and evaporation rates, and therefore, general circulation, production rates of deep and intermediate waters, etc. In the shallower areas, temperature rise might establish stratification of the saltwater masses, especially during the summer months, which will affect the sediment depositional regime in and out of the bays, causing blocking of navigation channels. Stratification would negatively affect the primary producers of the eutrophic zone, which initially might benefit from the warmer environment but will be adversely affected by oxygen depletion. High summer temperatures might lead to frequent anaerobic conditions in the polluted embayments (e.g., Thessaloniki, Abuqir, and Izmir Bays).

IMPACTS ON THE COASTAL ZONE

A significant rise of sea level, coupled with storm surges and high tidal ranges, would cause the retreat of beaches and possibly the transformation of some lagoons into bays, the flooding of reclaimed lands, salt wedges to move farther inland in rivers, as well as direct damage to harbors, towns, and roads. The impact analysis of these effects is complicated, however, by the growing anthropic interference with natural environments and the enormously accrued economic value of the coastal regions.

Deltaic coasts that are shaped by marine processes can reform themselves after major storms, and can rise gradually in phase with the average rise of sea level. This response, however, is sharply curtailed if the tributary river(s) is/are dammed and/or diverted. The stretches of the shore that are already unstable or retreating will be even more so in 2025. As the level of the sea rises, a normal beach and barrier island would be expected to migrate gradually inland (Brunn and Schwartz, 1985). Actual examples of this recession are available from the upper Adriatic and the Nile Delta coasts (Sestini, 1988a and 1988b).

In terms of physical impacts, increases of up to 30 cm should be considered to be moderate, because they could be coped with by gradual adjustments to existing coastal defenses and by acceptance of modest losses. Higher water levels in the lagoons and the flooding of estuaries and canals, especially if associated with land subsidence (e.g., Romagna, Italy) would continue. The beaches in most countries would continue to retreat, in spite of—and (in some cases) because of—defense structures. Greater increases (more than 50 cm), however, at least locally would have catastrophic consequences, involving hard economic decisions about the cost of coastal protection and political decisions about what to protect and what to abandon. Main concerns would be wave attack on harbor structures, the retreat of the headlands, the flooding of the residential and industrial quarters, and the management of the lagoons.

IMPACTS ON RAINFALL AND WATER RESOURCES

With regard to rainfall, the most important climate change would be the northward shift of winter cyclone patterns affecting the western and central Mediterranean. There might be a deceleration of cyclone activity and more erratic rainfall, drier summers, and higher evapotranspiration rates. Air circulation to the mountain masses would, in principle, remain the same—i.e., greater rainfall would characterize the western Pyrenees, the Eastern Alps, the western Balkan mountains, and the mountains of the Near East. The areas of lesser reliable rainfall (at present Africa, Sicily, southern Spain, and interior Turkey) might increase and shift northward. Overall, rainfall is expected to decrease in the south (Wigley, 1988).

Precipitation and evaporation over the Alps are not expected to change, but larger areas will be frost-free in winter, and less water will be stored as snow. This would lead to the retreat of the snow line (upslope by ca. 500 meters); the disappearance of the eastern alpine glaciers, and a 70–80 percent reduction of the western glaciers. Lesser and more erratic precipitation would cause reduced ground-water recharge (also due to lower percolation rates) and, therefore, lower ground-water levels and spring discharge. Decreased percolation would result in greater flood risks as well as higher sediment loads. There would be greater sedimentation in channels, with possible increase of braided versus meandering streams. The lifetime of reservoirs would be reduced. The cost of maintaining a sufficient amount of good-quality drinking water would increase, because of salinization and waterborne environmental risks (pollution, diseases).

Actual evapotranspiration in the region will increase by around 10 percent when mean air temperature rises by 1.5°C. This will result in at least a 10 percent decline in river flow and a corresponding increase in freshwater salinities. Potential evapotranspiration and open-water evaporation will rise by at least 10 percent. Despite an increased need for irrigation water, the average storage in the reservoirs will fall by up to 25 percent due to decreased river flow and precipitation and increased evapotranspiration; reservoirs will be nearly empty up to 19 percent of the time. An expected 25 percent filling of the reservoirs with sediment will seriously increase the water supply problems, with mean storage falling to around 60 percent of the projected levels under present conditions.

Climate zones may shift northward, thus increasing the length of summer at the expense of the other seasons. Increased variability and patchiness of the rainfall may extend summer aridity. Scattered rainfall may totally disappear during the warm season and may be transferred to winter. Reduction of rainfall during the hot summer period may cause deficiency in soil moisture, thus degrading the soil structure and agricultural fertility. Moreover, the reduced runoff could cause seasonal salt accumulation in the topsoil of several reclaimed lowlands.

Impacts on Soils

There is a great diversity of soil types in the Mediterranean region, reflecting differences in major soil-forming factors, one of which is climate. Some soil parameters are particularly sensitive to temperature and rainfall changes—e.g., soil composition and salt balance, chemical processes, and supply and breakdown of organic matter. The expected climate changes should not result in a major shift in the boundaries of the main soil types (Imeson and Immer, 1988).

Evapotranspiration and any decreases in the rainfall duration and intensity would increase salt accumulation. This would particularly affect areas where annual rainfall is less than 600 mm. Areas with salt and sodic conditions will expand, because of greater evaporation and decreased water precipitation and runoff, resulting in the slaking and dispersion of the soil's surface.

The impact of climate change on land degradation in the Mediterranean region will be most serious in areas where soils have an inherently high erodibility, in regions already under environmental stress, and in drier regions. Forested areas will also be adversely affected by the increased frequency of fire. The direct impacts on degradation resulting from changes in the magnitude and distribution of precipitation could be extremely important, but no information is available concerning precipitation changes. An increased temperature, by influencing the mineralization of organic matter and the form of organic soil material, the water balance, the salt balance, and the soil temperature will impart to the soil an increased susceptibility to physical degradation. Special attention is given to the effect of organic matter on soil stability and infiltration in areas having silty and sandy soils. Poor physical properties are likely to be caused by increased areas affected by clay dispersion. Gully erosion and piping could spread into areas that develop slightly drier conditions as a result of quantitatively small changes in the chemical composition of the soils (Imeson and Immer, 1988).

To assess the impact of climate change, relationships should be established between climate parameters and "climate-sensitive" processes. Threshold conditions should be identified by laboratory experiments and by field investigation along climate gradients. The "site-specific" impacts of climate change will determine the exact effects of degradation and erosion. Local studies will have to be made to establish exactly how site-specific factors determine the impact of general trends.

IMPACTS ON ECOSYSTEMS

Aquatic ecology is likely to be affected profoundly by temperature rise. Shallow onshore marine areas would become warmer and more saline—locally, hypersaline. In the ocean a 2°C rise in air temperature would result in a water temperature rise of 0.8-1.5°C down to 200 meters between Lat. 30°N and 30°S; surface currents would change over large parts of the oceans, possibly also in the Mediterranean. Conditions of fish stock and other biological parameters would be dramatically altered. In some areas, even a 1°C rise might have a marked adverse effect on fish life because of changes of oxygen concentration and water chemistry.

Aquatic species have different temperature tolerances. Thus, assemblages could change in consequence of removal of competition. Cold-water species would be forced to migrate or would disappear, and sea-river species would be adversely affected by alteration of coastal physiography and inland hydrology. The impacts of higher temperatures on inland waters might include algal blooms, massive fish kills, and the invasion of diseases (e.g., bilharzia, malaria).

Changes in seasonal rainfall distribution patterns could have significant impacts on natural vegetation; significant changes would have dramatic effects. An increase in the mean annual evapotranspiration of 180-220 mm would have a slight impact on natural vegetation and crops, but it could be significant in areas where climate or soil conditions are marginal with respect to types of vegetation or crop. One may also expect a slight shift in vegetation belts due to increasing aridity. Expanding desertification at the margins of the Sahara and Near-East deserts will happen in any case as the result of the exponential growth of population. Climate change would just aggravate the phenomenon (Le Houérou, 1988).

A general 2°C warming would lead to a shift of the natural range of species by 300–500 km northward and 300 meters in altitude. In the Alps, ecosystems would move 600–700 meters upward; evergreen species of oak would expand in the mixed woodlands at lower altitudes on the southern and eastern margins of the chain.

Forests would suffer from the increased temperature and aridity. The longer periods of drought would affect forest species that survive at the limit between semiarid and humid conditions, shifting their occurrence to higher altitudes. Forests of deciduous trees require ample moisture during the growing season; therefore, many species would disappear. The coastal plantations would suffer from salinization and, probably, remobilized sand dunes. The Mediterranean maquis cover could be affected by desertification. Finally, forest fires would become more frequent, also involving higher areas than at present.

Nature conservation would require reassessment and new policies. The protection of species through the maintenance of present natural conditions would be increasingly difficult, if not impossible. In some environments, only species adapted to unpredictable, rapidly changing environments could survive; rare species living in restricted ecological islands might not be able to migrate. Bird migrations would be affected by higher temperatures in the more boreal regions and by the changed ecosystems of their traditional staging and wintering locations.

IMPACTS ON AGRICULTURE AND FISHERIES

Weather fluctuations (temperature, heat waves, availability of water in the plant's growing stages, hail or heavy rains in the ripening stages) would affect several Mediterranean crops (wheat, soybeans, sugar beets, tomatoes, tobacco, citruses, and other fruit trees). Change in winter temperature would significantly affect areas where winter temperature limits plant growth—that is in most of the Mediterranean European highlands, and in the mountainous and continental areas of northern Africa and the Near East. For instance, change in winter temperature would increase the areas of cultivation of cold-sensitive crops, such as olive, citruses, winter cereals, and vegetables. Agriculture is likely to change toward even more intensive irrigation and use of greenhouses, at least in many areas. Nevertheless, warmer winters and severe water deficits would threaten the existence of tree cultivations (e.g., olives, nuts) that require a dormant period at relatively low temperatures. Crop plants would be adapted by selection of different strains (Le Houérou, 1988).

Soil fertility should tend to decrease, with fewer nutrients being available to the plants because of increased soil salinity. Irrigation would become increasingly necessary, but also more difficult and expensive, requiring better soil drainage. Cultivated areas in floodplains could be affected by a greater incidence of floods and by changes in channel morphology. In a globally warmer climate, some tropical and subtropical plant diseases would move north, and the distribution of insects and pests would be altered. This would necessitate new biological and/or chemical controls of pests and pathogens.

IMPACTS ON SOCIETY

Climate change should not affect the distribution and dynamics of human population in the littoral zones, because the natural growth of the population will continue to follow the present trends in the individual countries. Those trends are a slowly growing (perhaps static and locally decreasing) population on the northern Mediterranean coasts, and large increases in the countries of the southern coast. Migration to coastal areas could accelerate in the south due to increased desertification in the interior (Baric and Gasparovic, 1988). According to the five Blue Plan scenarios, in the year 2025 about 200–220 million people will live in the coastal zones, 75 percent of whom will live in cities.

Any foreseeable change in temperature would have an almost negligible impact on the environment compared to the demographic explosion. Nevertheless, sea level rise would considerably affect the economy and well-being of many countries, especially because many low coasts will increasingly experience physical instability due to sub-residence and river sediment starvation. An increase in the frequency and intensity of storms and of storm surge flooding would present major risks. Major expenditures would be required to control longshore drift and beach erosion. The main concerns include greater wave attack on harbor structures, retreat of headlands, and the management of lagoons.

Expected demographic and economic changes in Mediterranean coastal zones vary considerably. In the Ebro Delta, a temperature increase of 1.5°C and a sea level rise in the range of 20 cm would have much less effect on the system than the human-induced modifications. Nevertheless, these changes would increase actual erosion processes and lead to more frequent flooding of the wetlands, increasing their salinity and destroying the present flora and the nesting grounds for migratory birds. As the coastline retreats, the bays and lagoons gradually would be closed, affecting the area's marine productivity (Marino, 1988).

In northwestern Italy and in the Gulf of Lion, settlement patterns should change little because of low population growth. The main concern for regional management would be the availability of water resources. In France, most of the large urban centers (Perpignan, Narbonne, Béziers, Montpellier, Nimes, Arles) are built back from the shore and thus are protected from any serious impacts of sea level rise. On the other hand, the coast, with its tourist resorts and harbors, is particularly vulnerable due to the narrow strip of sand and the low altitude of the dune ridges (Corre, 1988).

In Italy, the main threats will be to the survival of Venice (and other towns of artistic-historical importance), to the tourist industry, to the activities of important harbors, and to specialized agricultural production. It might be more economical to turn at least parts of the reclaimed subzero-level lands back to their original lagoonal state, in favor of fishing, which is at present a more efficient and remunerative activity than agriculture. Lagoons and marshes also could act as buffer zones between the open sea and higher land, as well as nature reserves. Industrial and other activities in the areas less than 1 meter above the sea level at present would probably move gradually inland without excessive disruption (Sestini, 1988b).

In Greece, in the greater Thessaloniki area, the damming and isolation of the Thessaloniki Bay may become a necessary "buffer zone" in order to diminish the impacts of sea level rise on the low-lying urban and industrial coastal area. The bay would be transformed into a controlled lagoon, with essential navigation outlets, and would not negatively affect the greater Thermaikos Gulf marine environment, as saltwater circulation and the sewage output regime would remain almost unaffected. Otherwise, sea level rise and sea surges would cause significant damage along the whole coastline, as waves would easily overtop the present sea barriers fronting the reclaimed agricultural land, and the cement sea wall along the city of Thessaloniki. The beaches at the eastern end of the bay might gradually disappear due to high erosion, producing significant economic effects on recreational land use (Georgas and Perissoratis, 1988).

In the Nile Delta, the nature and extent of climate impacts will depend largely on the degree of coastal development during the next two to three decades. Intensified land use in the coastal zone is inevitable, due to the continued growth of population and the consequent need to augment food production through the further extension of land reclamation and of lagoonal fishing. These developments would place increasing stress on water supplies. The most serious direct negative effects of sea level rise could be on ports, lagoonal fishing, and lowland agriculture; indirect effects would be felt by population centers that are tied to port- and agriculture-related industries. Therefore, the main impacts of economic significance are those that impair the efficiency of harbors and the proper management of lagoonal fisheries and lowland agriculture. Alexandria would lose its attraction as a summer resort city, but the recreational use of beaches would not be threatened elsewhere (Sestini, 1988a).

In northern Tunisia, the whole area is at present adjusting to a period of accelerating change. Canalization, deforestation, and agricultural improvements have all had demonstrable effects on the Ichkeul-Bizerte Lakes. A scheme to construct more dams on the rivers flowing into Ichkeul between 1983 and 2000 could even more dramatically change the hydrology and ecology in this area. Overall, existing environmental problems are likely to be exacerbated; agriculture will suffer; inland and lagoon fisheries may have already disappeared through the impacts of the dam project; sea fisheries may benefit slightly; industry will be largely unaffected; water resources will decline in both quantity and quality; settlements will suffer through their foundations and sewers; and the quality of urban life may decline through an accelerated influx of farmers abandoning the countryside (Hollis, 1988).

Mitigating the adverse effects throughout the Mediterranean would require increased expenditures for:

- The protection of the low coastal areas against sea level rise.
- The protection of freshwater resources.
- The reconstruction of wastewater systems.
- The production of food and other agricultural products.

The costs of alleviating the consequences of climate change might be easily met in countries with higher national incomes. Poorer, developing countries may experience great difficulties in funding the necessary projects to alleviate (or at least temporize) the expected impacts.

MAIN FINDINGS OF THE MEDITERRANEAN TASK TEAM

With an assumed temperature increase of 1.5°C by the year 2025, potential evapotranspiration will increase throughout the Mediterranean, coupled with a possible decrease in precipitation in the south and an increase in the north. Hot, dry summers and exceptional events of drought or rainfall and floods, marine storms and tidal surges, and water stagnation and eutrophication could increase in frequency.

A 1.5°C increase in temperature would lead to an increase in land degradation, deterioration of water resources, decline in agricultural production and damage to natural, terrestrial, and aquatic ecosystems. It could also alter marine circulation in both the Mediterranean and the Atlantic, thus affecting marine productivity and the pattern of pollutant dispersal.

The future impacts on Mediterranean society of nonclimate factors (e.g., population increases, present development plans) may far exceed the direct impacts of climate change. Nonclimate factors will cause continuous increases in society's vulnerability to climate stress, particularly in the south. Together, these demographic and climate changes should increase the probability and hasten the occurrence of catastrophic events.

It is particularly difficult to forecast the effects of climate change on agriculture, beyond concluding that irrigation systems would suffer increasing stress, and soil degradation would reduce yields in rain-fed systems. Salinization of irrigation water would have negative consequences on sensitive grain yields. Consequently, new varieties of crops have to be introduced and adapted to the new natural settings and yield standards.

A global, eustatic rise in mean sea level of about 20 cm by 2025 would not, in itself, have a significant impact in the Mediterranean, except locally (e.g., lagoons). However, local sea level changes could be up to five times this amount because of natural land subsidence, enhanced by excessive ground-water withdrawal. Negative effects of this impact will be felt in low-lying areas, deltas, and coastal cities.

Most of the deltaic lowlands of the Mediterranean Sea are experiencing serious environmental problems because of agricultural, industrial, urban, and tourist developments over the last two decades. Problems range from water pollution and salinization to land subsidence, shoreline erosion, and restriction and deterioration of wildlife habitats. These problems will be increased by adverse socioeconomic conditions, the effects of which will be superimposed upon those of climate change.

Generally, marine and land weeds are expected to benefit from a warmer, CO_2-richer atmosphere. Flora and fauna of the wetlands would be forced to gradually adapt to changed conditions, which might be crucial for species with low tolerance to high salinities. As bioclimatic zonation would gradually shift northward, several species would migrate to the north, and insect populations might increase. Conditions would be favorable for increases in agricultural pests, bacteria, and diseases, especially in the swamps.

RESPONSE STRATEGIES

To develop a strategy for responding to the impacts of change, it is essential to identify those parts of the Mediterranean coastal regions where knowledge is still inadequate.

Regarding changes in sea level, prospective actions can be either preventive or reactive. For example, entire coasts and lagoon margins can be walled in, or choices must be made between irreplaceable coastal uses (e.g., national and military harbors, towns of historical-artistic value, lagoonal resources, specialized agriculture) and adaptations. Examples of such reactive actions would be (1) shifting land uses, (2) adopting a different approach to beach recreation (i.e., less urbanized), and (3) replacing extensive, uneconomical crops in low-lying lands with lagoons destined for aquaculture and nature reserves. The lagoons would act as a buffer belt, since their inner margins could be more easily protected than the exposed coast.

The immediate task should be to identify all "high-risk" areas and to reexamine the present factors of coastal dynamics in the context of increasing air/water temperatures and sea levels. Storm-impact maps should help provide a scientific basis for proper coastal zone protection. Engineering solutions, such as dikes and walls, are not likely to represent a realistic long-term solution to the problem of rising sea level, except in very special cases. The coastal dynamics of erosion and deposition, the relative life span of most human installations, and the possibility of providing complete protection for small areas of special importance mean that adaptation, evolution, and land-use change most likely will represent the most appropriate responses to sea level rise.

Clearly, the first need is to develop a realistic sea level rise scenario, and the second is to determine the physical impacts on inshore areas.

Close attention needs to be paid to the conservation of soil, ground-water, and wetland resources in the Mediterranean, because they contribute substantially to environmental stability. The adverse effects on downstream human settlements and ecosystems of large dam schemes have not been considered sufficiently in past planning. Future water management plans must be scrutinized more closely in relation to climate change.

Studies of the frequency of extreme events (high temperatures, high and low precipitation events, storms surges, etc.) and how these frequencies relate to mean climate conditions are needed to help predict probabilities of occurrence. The implications of climate impacts for some regions and processes are highly complex. Therefore, systems analysis seems to be the best approach to their study.

Finally, organizational and legal instruments should be developed to control coastal development, land reclamation, and ground-water exploitation. Lowlands could be analyzed and zoned in high-, medium-, and low-risk categories.

RESPONSES OF NATIONAL AUTHORITIES TO STUDY FINDINGS

Three of the completed site-specific case studies (deltas of the Nile, Po and Ebro) prepared by the Mediterranean Task Team were presented to national seminars in 1988 and 1989. Although the seminars were found interesting by their participants and the quality of the studies was believed to be high, the seminars and the studies had very little impact on national policies, even in cases when the seminars were well attended by numerous local experts and by representatives of national authorities (e.g., in Cairo). Due to insufficient interest on the part of the national authorities, two of the three remaining site-specific case studies prepared by the Mediterranean Task Team (Thermaikos Gulf and delta of the Rhone) have been awaiting presentation to national seminars since 1988.

The study of the potential impacts of expected climate change was successfully incorporated into four coastal zone management projects (Izmir Bay, Island of Rhodes, Kastela Bay and Syrian coast) being carried out in the framework of the Mediterranean Action Plan. The general conclusion was that in spite of the high quality of the Task Teams's products, the impact of the Task Teams' work on national authorities and international bodies and programs was, in most instances, below the expected level. This was largely due to the strategies used for:

- Preparing regional overviews that generally lacked a strong involvement of national authorities.
- Selecting sites for site-specific case studies on the basis of the importance or vulnerability of the site as perceived by the Task Teams, and without close consultation and involvement of "end users" in the preparation of the case studies.

PRINCIPLES FOR PREPARING FUTURE SITE-SPECIFIC CASE STUDIES

The experiences of the Regional Task Teams were reviewed in November 1990 at the Joint Meeting of the Coordinators of the Regional Task Teams on Implications of Climatic Changes (UNEP, 1990). At that meeting, the participants agreed on the following elements of a general strategy for preparing future site-specific case studies:

- Case studies should be prepared either at the explicit request of the prospective end users or after a firm confirmation of support has been received from a potential user of the case study. In both cases, the intended use of the case study should be clearly stated.
- The potential end user(s) should be involved in formulating the study's outline and should participate in carrying out the study—i.e., the study should not be done "for him" but "with him," with the assistance of the Task Team.
- If at all possible, the study should be prepared within the framework of an integrated coastal zone management plan.

- Each case study should have a section containing specific recommendations for policy options and measures that may mitigate or avoid the negative implications of the predicted impacts of expected climate change.

- The studies' results and recommendations should be clear, unambiguous, and easily understandable.

- The studies should not contain irrelevant material—i.e. material that is not being used for supporting the studies' conclusions and recommendations.

- No study should be considered complete if it is without social and economic considerations.

- The counterpart representative of national authorities, associated with the work of the Task Team, should be made responsible for ensuring the coordinated involvement of relevant national authorities in the study's preparation.

- The counterpart representative of local authorities, associated with the work of the Task Team, should be expected to contribute to the preparation of the study, at least in kind and services.

REGIONAL SCENARIOS OF CLIMATE CHANGE IN THE MEDITERRANEAN BASIN

Acting on a recommendation of the first meeting of the Mediterranean Task Team in 1988, the Climate Research Unit of the University of East Anglia developed, with the financial support of UNEP, scenarios for climate change in the Mediterranean region (Palutikof et al., 1991). The results of this project concentrate on predictions in temperature and precipitation changes, and will help considerably in the preparation of the second generation of site-specific case studies.

The basis of these scenarios was the grid-point output from the following four General Circulation Models (GCMs): UK Meteorological Office (UKMO), Goddard Institute of Space Studies (GISS), Geophysical Fluid Dynamics Laboratory (GFDL), and Oregon State University (OSU). The standard approach was to run the model with a nominal "preindustrial" atmospheric CO_2 concentration (the control run), and then to rerun the model with doubled CO_2 (the "perturbed" run). The models are allowed to reach equilibrium before the results are recorded.

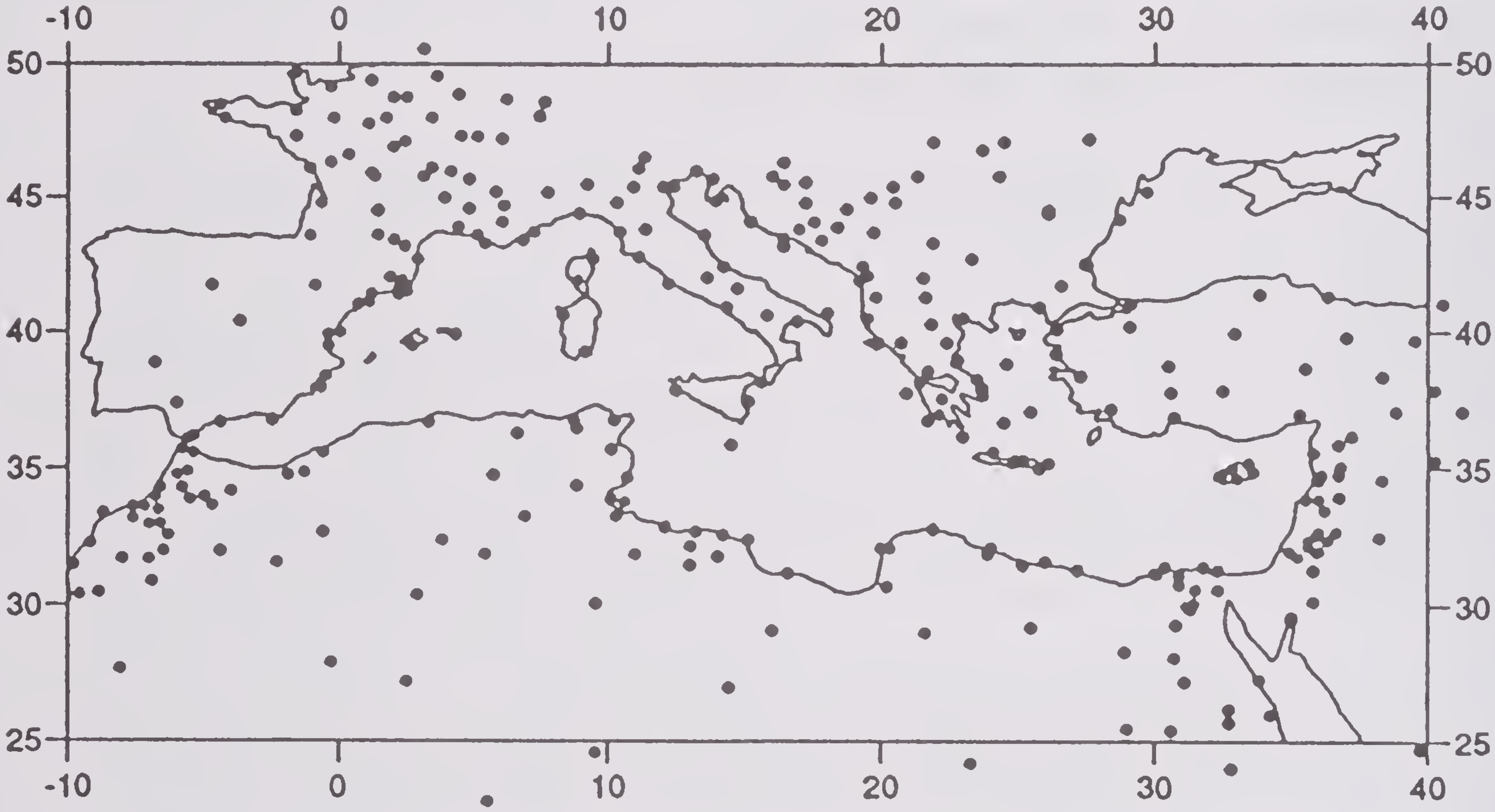
As a test of model accuracy, the control-run results were compared with observations for grid points in the study region. Two climate variables were examined: mean sea level pressure (MSLP) and precipitation. On the MSLP tests, the most realistic models were the GISS and UKMO GCMs. However, the GFDL model produced the most accurate simulation of precipitation.

Seasonal and annual scenarios of the regional changes in temperature, precipitation, and MSLP, based directly on GCM grid-point output, have been developed. Since no single GCM can be identified as being always the best at simulating current climate, there is little merit in presenting scenarios of climate change based on any single model. Therefore, the approach of Wigley et al. (1992) was adopted, whereby the information from the four models was combined into a single scenario for each variable. One problem with this approach was that a bias may be introduced by the different equilibrium responses of the individual models. To avoid this, the results were expressed in standardized form, as the change per unit increase in the annual, global-mean equilibrium temperature.

The direct scenarios indicate that the temperature change due to the greenhouse effect for the Mediterranean Basin should be similar to the global response. Precipitation is shown to increase in autumn and winter but decrease in summer and, particularly in the eastern Mediterranean, in spring also. The mean changes are: in winter, around +3%/°C, and in summer, around -3%/°C. However, confidence in the model scenarios of precipitation is low because of the uncertainty associated with the GCM results.

The degree of regional detail in the direct scenarios of climate change is constrained by the coarse resolution of the model grid. This is inadequate for many purposes, especially in areas of high relief. Methods developed by Kim et al. (1984) and Wigley et al. (1990) were adopted to produce a set of high-resolution scenarios based on the statistical relationship between grid-point GCM data and observations from surface meteorological stations. The networks of temperature and precipitation measuring stations used for scenario building are presented in Figure 2. Temperature and precipitation scenarios, based on the combined standardized output from the four GCMs, were constructed.

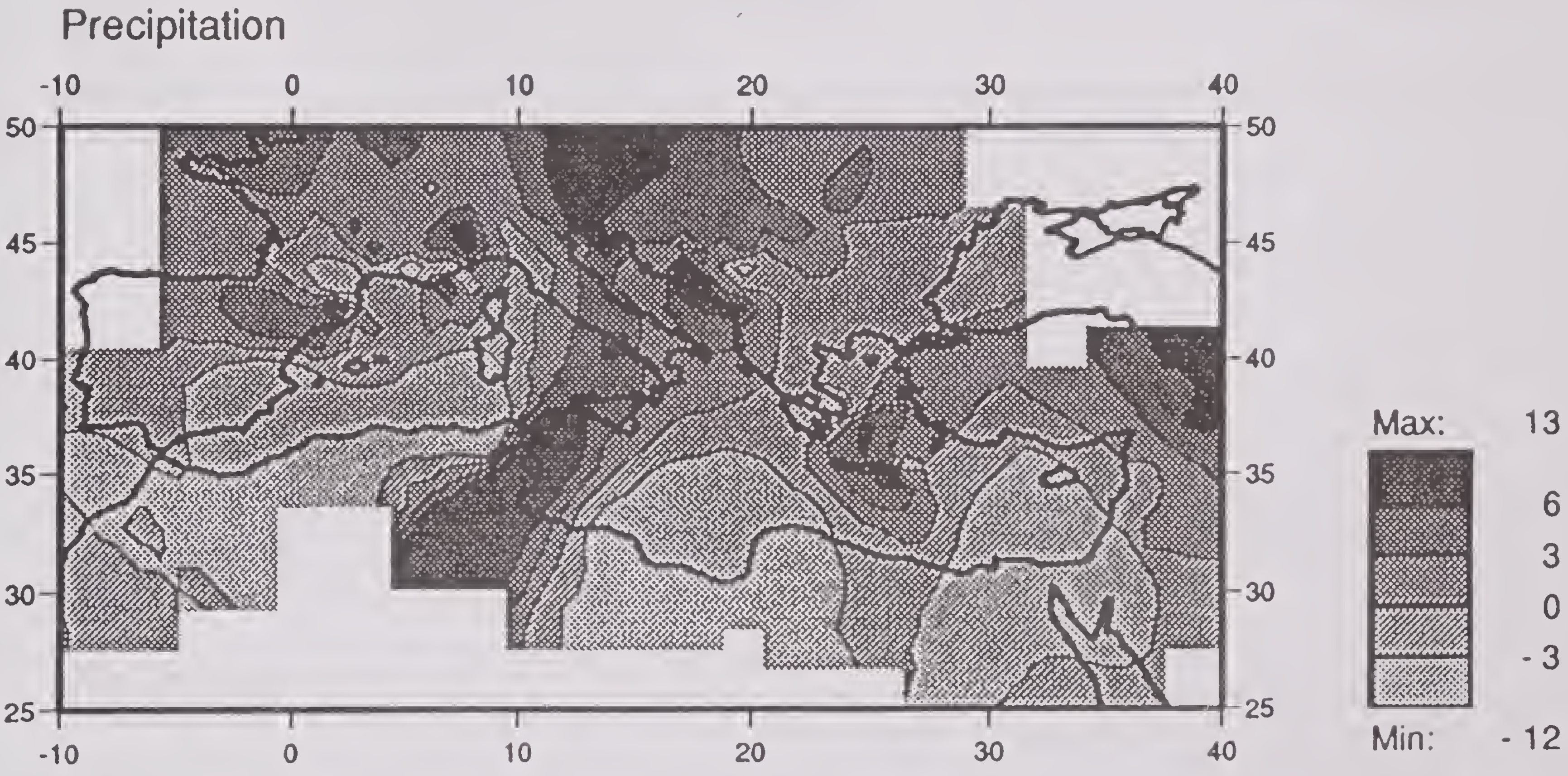
FIGURE 2. NETWORK OF TEMPERATURE (ABOVE) AND PRECIPITATION (BELOW) MEASURING STATIONS



Source: Palutikof et al., 1991.

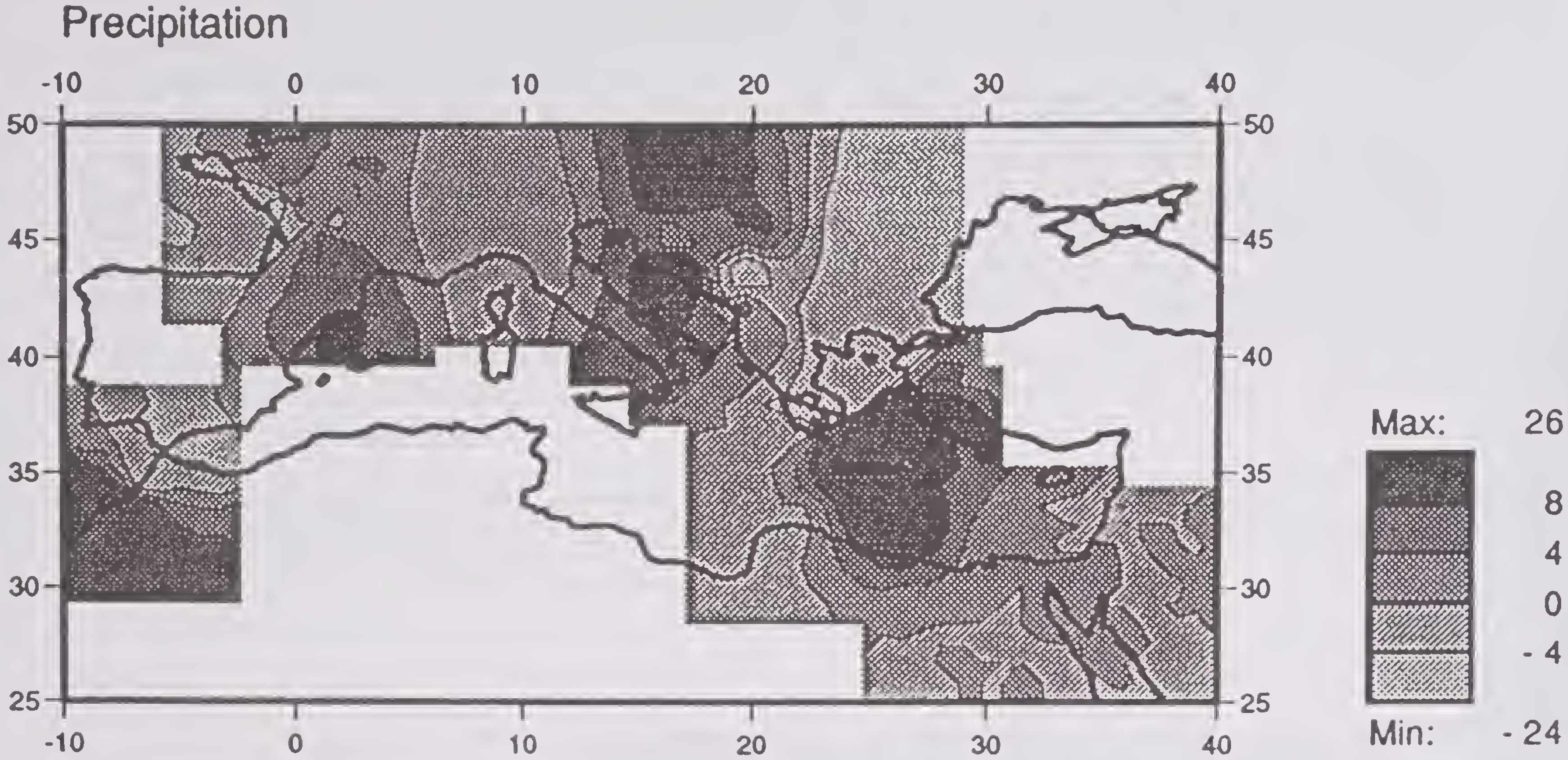
The temperature scenarios constructed in this way are likely to be a considerable improvement on the direct scenarios. The patterns were broadly similar, but the greater spatial resolution added substantially to the knowledge of the changes indicated by the GCMs for this geographically complex region. The greatest sensitivity was found in the area to the north of the Mediterranean Sea, with the northern coastline picked out as a zone of rapid transition. The scenarios of precipitation are more difficult to evaluate. The high level of uncertainty associated with the direct scenarios for this variable was noted. Here, a second level of uncertainty was added, since the relationship between the point precipitation anomalies and the regionally averaged predictor variables was generally weak: less than 60 percent of the variance in point precipitation is explained by the predictors over most of the region and most of the year. Therefore, the confidence in the subgrid-scale scenarios of precipitation must be low. Examples of subgrid-scale scenarios of temperature (°C) and precipitation (mm) change per °C change in global-mean temperature are presented in Figure 3 for annual changes and in Figure 4 for changes in summer.

FIGURE 3. SUBGRID-SCALE SCENARIOS OF ANNUAL TEMPERATURE (°C) AND PRECIPITATION (MM) CHANGE PER °C CHANGE IN GLOBAL MEAN TEMPERATURE



Source: Palutikof et al., 1991.

FIGURE 4. SUBGRID-SCALE SCENARIOS OF SUMMER TEMPERATURE (°C) AND PRECIPITATION (MM) CHANGE PER °C CHANGE IN GLOBAL MEAN TEMPERATURE



Source: Palutikof et al., 1991.

So far, regional scenarios of change were discussed in the mean value of a climate variable. Of equal importance to the impact analyst, particularly with respect to precipitation, are the implications of these changes for the occurrence of extremes—the frequency and severity of droughts and floods. Such information might be obtained directly from GCMs, but the uncertainties associated with this approach were already indicated. Therefore, an alternative approach was adopted, based on a two-part statistical model of precipitation. This combines a first-order Markov chain, to describe the precipitation occurrence process, with a gamma function to describe the distribution of precipitation amounts on wet days.

The model was applied to the daily precipitation records from 10 stations in the region. Validation was performed by comparing observed characteristics with those derived from model simulation runs. Then a perturbation equivalent to a change in the mean precipitation of 10 percent (both an increase and a decrease) was applied. To examine the implications for extreme events, the change was examined in the maximum and minimum precipitation amount per wet day, and in the length of wet and dry spells. It was found that the characteristics of extremes changed by a much greater amount than the initial perturbation of 10 percent. Changes on the order of 20 percent were not unusual. This has particular implications for the Mediterranean basin, where water supplies are already marginal for many agricultural and industrial activities.

The study has demonstrated the wealth of regional detail that can be extracted from coarse-resolution, GCM grid-point output by synthesizing modeled and observed data. However, the accuracy of any regional scenarios so constructed is constrained by the reliability of GCM results. The GCMs used in the present study are unable to reproduce accurately the characteristics of present-day regional climates, and this must cast doubt on their predictions of the future. Furthermore, the model results used here are derived from equilibrium response predictions, the spatial patterns of which may differ from the changes that will occur in a real, transient response world. For this reason, the scenarios presented in this study can only be taken as an indication of the range of possible changes that might occur as a result of greenhouse warming. However, the construction techniques used are of general applicability, and the quality of regional scenarios will improve as more accurate GCM predictions become available in the future.

THE MEDITERRANEAN STUDY: PHASE II (1990–92)

After completing the first phase of its work (in 1989), the Mediterranean Task Team started the second phase in 1990 with six new site-specific, second-generation case studies: Island of Rhodes, Kastela Bay, Syrian Coast, Izmir Bay, Malta Island, and Cres/Losinj Islands (Figure 1). This section describes the objectives, assumptions, outputs, and outline used in the second generation of site-specific case studies.

OBJECTIVES

The objectives of the case studies are:

- To identify and assess the possible implications of expected climate change on the terrestrial, aquatic, and marine ecosystems, populations, land-use and sea-use practices, and other human activities.
- To determine areas or systems that appear to be most vulnerable to the expected climate change.
- To identify options and give recommendations for planning and managing coastal areas and resources, as well as for planning and designing major infrastructure and other systems.

ASSUMPTIONS

For the specific purpose of the case studies, a sea level rise of 24–52 cm and a temperature elevation of 1.5–3°C by the year 2050 will be used, taking into account:

- The best available information, knowledge, and insights into the problems relevant to the study area, including major projects, planned or under consideration.
- The assumptions accepted at the Second World Climate Conference (1990)—i.e., an increased temperature of 2–5°C and sea level rise of 65 +/- 35 cm by the end of the 21st century.
- The results of the University of East Anglia's scenario analysis for the Mediterranean Basin with subregionally specific scenarios.

OUTPUTS

The outputs of the study will be:

- Identified impacts of predicted climate change and sea level rise.
- An assessment of the magnitude and implications of the identified impacts.
- Proposed policies and measures to mitigate or avoid the predicted consequences of expected climate change.

OUTLINE OF THE STUDY

The following outline for each study is used, with possible slight modifications due to local specificities:

- Executive summary

- 1. Introduction
  - 1.1. Background
  - 1.2. Basic facts concerning the study area
  - 1.3. Methodology and assumptions used in the study

- 2. Identification and assessment of the possible consequences of climate change
  - 2.1. Climate
  - 2.2. Lithosphere
  - 2.3. Hydrosphere
  - 2.4. Atmosphere
  - 2.5. Natural ecosystems
    - 2.5.1. Terrestrial
    - 2.5.2. Freshwater
    - 2.5.3. Marine
  - 2.6. Managed ecosystems
    - 2.6.1. Agriculture
    - 2.6.2. Fisheries
    - 2.6.3. Aquaculture
    - 2.6.4. Sylviculture
  - 2.7. Energy and industry
  - 2.8. Tourism
  - 2.9. Transport and services
  - 2.10. Health and sanitation
  - 2.11. Population and settlement patterns

- 3. Synthesis of findings
  - 3.1. Present situation
  - 3.2. Major expected changes and their impacts

- 4. Recommendations for action
  - 4.1. Preventative policies and measures
  - 4.2. Adaptive policies and measures

- 5. References

All six second-generation case studies are ongoing and should be finalized by the end of 1992. Scenarios for the temperature and precipitation changes for the area of the Island of Rhodes, Kastela Bay, and Malta Island were developed by the Climate Research Unit of the University of East Anglia and are being used in respective case studies. Scenarios for the Syrian coast, Cres/Losinj Island, and Izmir Bay are being prepared.

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CLIMATE CHANGE AND SEA LEVEL RISE IN THE WIDER CARIBBEAN AND ADJACENT SEAS

Beverly A. Miller
United Nations Environment Programme
Caribbean Environment Program
Kingston, Jamaica

BACKGROUND

The history of the environment and man is related to the earth's climate and its variability in time. How to assess its impact has become a challenging issue.

Climatologists use a variety of means to describe the earth's climate for the last 100 and 1,000 years. They show that the earth's temperatures have varied significantly since the 15th century, when the Caribbean Sea was discovered and Europe was in a cold period known as the Little Ice Age. At present, the earth's climate is warmer than it has been in the last 1,000 years, but by no means as warm as it was in several past epochs, as records of the last million years indicate.

The United Nations Environment Programme (UNEP), through the Regional Seas Programme and the Caribbean Environment Programme, has extended its marine environmental interests to include the impact of climate change in the region. UNEP is considering the results of the WMO/ICSU/UNEP meeting at Villach, Austria, in 1985, where it was accepted that an equilibrium global warming of 1.5–4.5° C and a global sea level rise of 0.20 to 1.4 meters could be forecasted, due to an expected doubling of the greenhouse gases between the beginning of the Industrial Revolution and the year 2030. For several reasons, this situation may or may not be realistic for the Intra-American Sea (wider Caribbean and adjacent seas).

For the Intra-American Sea, for the longest records, sea level has risen on average at about 0.36 cm/year over the last 30 years. The values ranged from 0.14 cm/year (Bahamas) to +1.0 cm/year (Texas). This high spatial variability makes a regional average nearly meaningless. Regarding temperature, the 136-year record in Key West, Florida, shows that a rise in temperature occurred between 1890 and 1950, but the temperature over the last 30 years has been almost steady, at +0.3° C above the long-term mean. Nevertheless, other studies suggest that the temperature in the region is increasing.

With regard to the effects that temperature rise may have on the climate, an increase of 1.5° C in sea surface temperature could increase the number of hurricanes by as much as 40 percent and the maximum wind speed by 8 percent. Rainfall would continue to decrease, air temperature would continue to rise, as would surface wind speed and evaporation.

In the tropics, marine organisms live closer to their maximum thermal tolerance than those in more temperate climates. Although the 1.5° C temperature rise scenario could raise the summertime mean temperature to 30.5° C over much of the wider Caribbean region, most migratory organisms are expected to be able to tolerate such a change. Littoral, supralittoral organisms, such as mangroves, are adapted to withstand high temperature, and unless the 1.5° C increase affects the reproductive cycle, the temperature elevation could be meaningless.

Climate change could have socioeconomic impacts on both the microeconomic or localized level, and the macroeconomic or economy-wide level. The smaller or the more coastal-oriented an economy is, the greater could be expected the impact of sea level rise. The Intra-American Sea, with its small-island-based economies, such as fishing/or tourism, is particularly vulnerable to the physical changes associated with changing climate. Ironically, some climate changes may benefit certain sectors of an economy, like the construction industry, while being detrimental to others, like tourism because of beach erosion.

EFFECTS ON COASTAL ECOSYSTEMS

In the wider Caribbean region, there are four major river deltas: the Mississippi (USA), the Río Grande (Mexico/USA), the Magdalena (Colombia), and the Orinoco (Venezuela). River deltas will be particularly vulnerable to erosion enhanced by sea level rise because the sediments are unconsolidated mud subject to subsidence and compaction. A shoreline could retreat up to several meters horizontally for each centimeter of rise in relative sea level. This could be translated into thousands of hectares of lost land. The problem could be exacerbated by potential increased storm activity, since most shoreline erosion occurs during storms, and by subsidence. Delta benthic systems, particularly sea grass beds, could be most affected or destroyed by the expected rise in relative sea level.

ESTUARIES

With respect to the estuaries, as with the deltas, the effect must be considered on a case-by-case basis in order to make meaningful impact assessments. Because of local uplift, areas could experience lower or higher sea levels. Many wetlands during the last 5,000 years have been able to keep pace with rising sea level. Where wetlands are bounded by steep-sided basins, as is the case in many of the Caribbean islands, it is unlikely that they will be replaced as sea level rises. On gentler island and continental floodplains, such as the northern Gulf of Mexico, the problem may be less severe.

COASTAL PLAINS

The primary effect on coastal plains will be increased flooding during storms (from raised sea level and/or from heavy rainfall). Shore migration will vary, depending on the substrate, and sandy beaches will be more affected than rocky coasts. A general rule could not be applied for the region because of such differences as tectonic displacement, beach structure, offshore bottom topography, and storm frequency and magnitude. Nevertheless, areas where subsidence is evident have to be carefully monitored, as it will exacerbate flooding.

CORAL REEFS

The second largest coral reef system in the world is found in western Caribbean Sea. There are also extensive reef systems in the Gulf of Mexico and the West Indies. Growth of individual coral organisms is estimated to be between 1 and 20 cm/year, depending on the species. Although not all reefs grow at these rates, some could keep pace with the rise in relative sea leve of 20 cm by 2025 if other factors do not alter growth conditions, such as storms, sedimentation, disease, rainfall, radiation, turbidity, overfishing, and mass mortality in algal grazers.

MANGROVES

Mangrove forests in the region are composed of five species, occupying about 3.2 million hectares, or some 15 percent of the estimated world total of 22 million hectares of mangroves. Because mangroves grow best in moderately saline environments, it is postulated that they can keep pace with relative sea level in rainy humid areas, but may be inundated and abandoned in more arid areas, particularly if inland retreat is not possible in terms of global climate change. Future changes in patterns of precipitation and catchment runoff may be more important than relative sea level. As for sea grasses, a 20-cm rise in sea level could not be expected to seriously affect the six common species, but if there are other changes in the quality of light, influence of herbivores, substrate, wave energy, or bottom slope, the beds may be damaged.

FISHERIES

The scenarios of 1.5° C and 20 cm increases by 2025 AD are not expected to create any significant changes in the fisheries, except in some shallow lagoons where hypersalinity may affect productivity. Increases in turbidity from erosion from higher water or river runoff could also harm productivity, particularly if juveniles have a critical dependence on salinity or temperature. The complexities of the ecosystem could be greatly affected by slight temperature changes, which will displace artisanal fishermen from traditional fishing sites.

SALTWATER INTRUSION

Saltwater intrusion is expected to have a large impact in the coastal plains. Islands usually have small, coastal aquifers, and sea level rise will degrade water quality in aquifers that have hydrological continuity with the sea and will affect the water supply, such as on the leeward side of small mountainous islands. Continental areas are not expected to be seriously affected. Differing permeability in aquifers can cause great variability in the effect of rising sea level. Relocation of wells, construction of weirs, water storage schemes, and barging of water are all possible socioeconomic responses. In low-lying lands that depend on well water, many municipal waters supplies, drainage, and sewerage systems will have to be modified.

SOCIOECONOMIC EFFECTS

The single-most important industry in the wider Caribbean region is tourism. Shoreline migration due to sea level rise will create new areas of economic benefit as new beaches are built. But the protection, replenishment, and stabilization of existing beaches, at least until major existing tourist investments are amortized, will come at a high cost. Navigation and port facilities normally have to be reconstructed and maintained, so a 20-cm rise in sea level is not considered serious. On the other hand, some nearshore roads, sea walls, and bridges will have to be increasingly repaired, and if the sea level rise is augmented by increased storm activity, the impacts will be serious, particularly in countries with marginal economies.

Oftentimes, the population growth is faster in areas most likely to be affected by sea level rise. Extreme weather events create serious public health problems, in addition to physical danger. Temperature and sea level rise are expected to affect human health. Many diseases and acute illnesses are associated with elevated temperatures, and water is a principal agent for many organisms that carry disease. Although only health-related costs are expected to increase in the region, the health-care delivery systems should keep pace with the climate-related impacts to the year 2025.

RECOMMENDATIONS

To strengthen quantitative information transfer to states, regional climate models nested in coupled ocean-atmosphere global circulation models are needed, along with long-term in situ monitoring programs, coupled with an active multidisciplinary research effort that examines the historical, geological, and archaeological records so as to supplement direct measurements. Understanding future shoreline migration should be the first priority in the region, based on current information, but if precipitation changes are markedly underestimated, the impacts on agriculture and coastal ecosystems could be far more important.

Ecologically speaking, the identification of the most vulnerable ecosystems requires more of a "micro-scale approach." Preparation of a regional map with a classification scheme showing areas and ecosystems most vulnerable to climate change is a massive, but necessary, undertaking. Sea grass beds, coral reefs, mangroves, and coastal lagoons are probably the most critical habitats to be mapped. Associated with critical habitats are species that use them as feeding and/or nursery grounds. Of vital concern to these critical habitats are climate-related impacts from sewerage and toxic wastes of nearby human population centers and agricultural regions.

On socioeconomic issues, it is important to note that some countries are already drafting measures for responding to the impacts of sea level rise. Costa Rica has already established new building setback laws for construction along the coasts. Individual governments must prepare for is a significant international migration of populations from highly vulnerable locales to areas where safety and the quality of life are deemed better. To prepare for such future changes, a catalog of institutional responses needs to be developed, along with specifications of conditions under which those responses should be implemented.

While many of the estimated impacts will be different from site to site, on a regional scale, vulnerability to most climatic changes is judged as being low to moderate. However, because of other pressures on the marine environment and society's efforts to deal with the effects of these pressures, vulnerability to climate change is increasing. In many cases, the future impacts on society of nonclimate factors may far exceed those from climate change. It is important for policy considerations to consider that climate change will exacerbate environmental changes already ongoing and documented in other studies.

From a climate perspective, a sea level monitoring network must be reestablished and must include marine meteorological data, geodetic leveling data, saltwater chemistry data, and ancillary site-specific information. Establishing and maintaining a modern sea level/weather observation network is absolutely necessary to document and ultimately forecast the impacts of climate change.

World Meteorological Organization

The Challenge of Sea Level Rise for the World Meteorological Organization

G.O.P. Obasi
Secretary-General
World Meteorological Organization

According to the (Intergovernmental Panel on Climate Change's IPCC's) First Assessment Report (1990), the mean global temperature has been rising since the end of the 19th century, and global sea level has risen by an average of 1–2 cm per decade over the same period. The majority of sea level rise appears to be related to the observed global warming. Thus, there are good reasons to expect that future warming will lead to an acceleration of sea level rise. The IPCC "Business-as-Usual" scenario indicates an average rate of global mean sea level rise of about 6 cm per decade over the next century (with an uncertainty range of 3-10 cm per decade). The predicted rise is about 20 cm by the year 2030 and 65 cm by the end of the next century. The latter figure could be as high as 110 cm, if no measures are taken to contain the continued emission of greenhouse gases into the atmosphere. Consequently, the rise of 12–40 cm expected over the next four decades will be comparable to or even much higher than that experienced over the past 100 years (10–20 cm).

The IPCC has continued to place strong emphasis on the issue of sea level rise. An account was given of the possible impacts on populations living in low-lying coastal areas, the implications of sea level rise for agriculture, and its effects on wetlands, water resources, and a host of other life-supporting systems and economic activities. Finally, the IPCC has also proposed adaptive measures, with an account of the environmental and economic implications of those measures. This workshop will focus on sharing experiences in (1) assessing vulnerability to sea level rise, (2) identifying adaptive response strategies, and (3) developing and implementing coastal management plans.

The effort directed to the question of changes in sea level is justifiably well placed. The sea is of such paramount social, economic, and scientific significance that all its facets must receive the attention of the world's scholars and of national and international scientific organizations and institutions.

For example, a major endeavor in the program of the World Meteorological Organization (WMO) is devoted to the promotion of our understanding of the ocean, with special emphasis on its interaction with the atmosphere and how that interaction affects the global climate system, which dictates the course of the global warming that is responsible for sea level rise. We have undertaken and continue to undertake special studies and research programs designed to enhance our understanding.

The World Climate Research Program, coordinated jointly by WMO and the International Council of Scientific Unions, manages the Tropical Oceans Global Atmosphere (TOGA) project.

TOGA's basic scientific objective is to develop the capability to predict changes in the ocean-atmosphere system on time scales of months to years. TOGA has two main components: measurement and mathematical modeling of the ocean-atmosphere system. An element of special relevance to this workshop in the measurement program is the TOGA Sea Level Network and the associated TOGA Sea Level Data Center at the University of Hawaii. In the tropical Pacific, nearly every island to which regular transportation is available has been equipped with a tidal gauge.

In the Marine Meteorology and Associated Oceanographic Activities Program, the WMO addresses two basic issues: a study of the interaction between the sea and the atmosphere, and the provision of services for maritime activities. The program, *inter alia*, continually develops and expands on a comprehensive and integrated marine environmental service, including sea-ice services and information exchange on marine technology and services. Within this program, the Integrated Global Ocean Service System (IGOSS) has been established. Planned and developed jointly by WMO and Intergovernmental Oceanographic Commission (IOC) of UNESCO, IGOSS was created to meet the requirements of marine user groups for the real-time collection of oceanographic data and for the provision of real-time oceanographic services, often in conjunction with national marine meteorological services. IGOSS includes two programs for the operational collection and processing of sea level data and the preparation of ocean basin-scale analyses of sea level anomalies: (1) the IGOSS Sea Level Programme in the Pacific and (2) the IGOSS Sea Level Pilot Project in the North and tropical Atlantic.

The threat of sea level rise presents a real potential hazard. The sea swells associated with tropical cyclones, hurricanes, or typhoons will become more intensified, and the associated flooding will create greater hazards than currently experienced in areas prone to these storms. Within its World Weather Watch program and its Research and Development program, WMO maintains a tropical cyclone subprogram in which more that 50 countries participate. The program is designed to increase our understanding of the physics of these storms, improve on methods of forecasting their occurrence, and create preparedness within the storm-prone countries in order to reduce the loss of life and property from these storms.

Sea level rise is expected to have very serious throughout the world:

- On the *island nations* of the world and their populations and their economic and other activities.

- On the huge *coastal cities* of the world and their inhabitants and their economic, commercial, and industrial activities.

- On the *low-lying coastal areas* surrounding our continents, those who inhabit them, the agricultural and other economic activities they are engaged in, as well as the critical role that these areas play in global ecology.

- On the *major deltas* of the world and their populations and their agricultural and other activities.

- On *global shipping infrastructure:* ports and harbors and related world trade and communication they sustain.

- On the *beautiful beaches* that sustain global tourism, and the revenue earned by nations from this important activity.

In addition, populations will be displaced, which may create environmental refugees, and agricultural land and freshwater systems will be lost through flooding and saltwater intrusion. Commercial, industrial, and marine transport will be affected as coastal infrastructures are increasingly threatened by damage from waves and storm surges, which will penetrate more and more inland.

The challenge of the sea must be viewed in the overall context of the threat of global warming. Any measures taken to combat or adapt to the challenge must be part of those designed to delay or adapt to that warming.

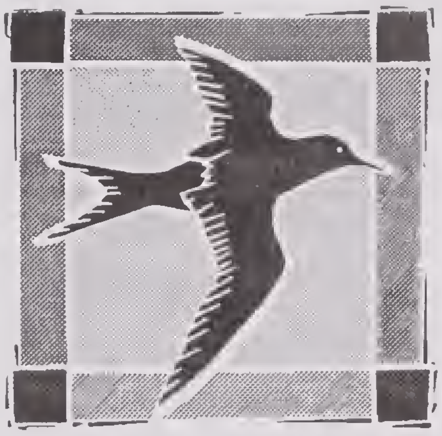
WMO has been concerned for many decades about possible alteration of the global climate system as a result of human activities. As far back as 1929, the International Meteorological Organization, the predecessor of WMO, had established a Commission on Climatology to address the issues of climate and its variability. By 1974, WMO established an Executive Committee Panel on Climate Change. This panel (not to be confused with the IPCC) was charged with studying the problem of emissions of carbon dioxide due to human activities and the possible effects of such emissions on the earth's climate. The panel's findings paved the way for WMO's subsequent actions on global warming.

The convening of the First World Climate Conference in Geneva during 1979 by WMO, the United Nations Environment Programme (UNEP), and the International Council of Scientific Unions (ICSU) gave great impetus to the climate issue as it led to the creation of the World Climate Programme by the WMO Congress. The World Climate Programme has four main components: the data and applications components are managed largely by WMO, the impacts and response component by UNEP and WMO, and the research component by WMO and ICSU. In view of the increasing importance of greenhouse gases to global warming, WMO, UNEP, and ICSU convened assessment meetings in Villach, Austria, during 1980 and 1985 and also charged the meetings to explore ways of furthering our understanding and management of the climate change issue.

The 1985 Villach meeting findings resulted in the establishment of the IPCC in 1988 by WMO and UNEP. The IPCC provides a mechanism that can continuously assess the emissions of greenhouse gases and their effects on climate. Furthermore, it provides a forum where governments exchange information on the complex issues of climate change, discussing its causes and impacts and possible response options to limit or adapt to it. Governments the world over have provided scientists who contributed to the writing of the IPCC First Assessment Report during 1990, and participated in its peer review process.

In that report, the IPCC put at the disposal of governments an array of possible policy options to limit or adapt to climate change. Governments now deliberating a Framework Convention on Climate Change within the Intergovernmental Negotiating Committee process would be well advised to take account of those recommendations. Many measures recommended by the IPCC are environmentally sound and economically beneficial in that besides addressing the issue of climate change, they also have other social and economic benefits.

The concern about climate change, global warming, and sea level rise is universally accepted. There are also measures suggested that if implemented, would reduce the rate of climate change. The urgent task facing our policymakers now is the pace at which they adopt and implement policies to limit climate change in a manner commensurate with the expressed concern about the adverse consequences of that change. Clearly, the world community should continue to develop an efficient and effective mechanism for improving the global monitoring and research of the atmosphere, the oceans, and, indeed, the whole global climate system.



OTHER RELATED STUDIES

QUANTIFICATION OF RESOURCES AT RISK TO SEA LEVEL RISE IN DEVELOPING COUNTRIES

Norbert P. Psuty and Neal Devine
Institute of Marine and Coastal Sciences
Rutgers—The State University of New Jersey
New Brunswick, New Jersey

ABSTRACT

This paper presents data and preliminary analysis of sea level rise risk assessments in seven developing countries. These data have significant implications for current international scientific, managerial, and policy efforts related to sea level rise. Almost without exception, the data sets reveal the potential for much greater local, regional, and national impacts than has been anticipated heretofore. Among numerous factors contributing to higher risk estimates are: (1) previous risk assessments have been based on a static concept of a global 1.0-meter rise in sea level, which ignores coastal system dynamics; (2) intertidal and estuarine regions throughout the world are extensively and intensively developed, and cultures and economies depend on the delicate balance struck with current rates of sea level rise; (3) a large proportion of potential impacts related to sea level rise will be associated with the ongoing, rapid expansion of urban/industrial development into increasingly hazardous areas; (4) to date, coastal defense strategies, economic and political commitment to coastal planning, and international scientific and technical transfer have had a poor record in most developing countries, and there exists little evidence for significant developmental policy change, despite increased knowledge concerning sea level rise.

INTRODUCTION

A greenhouse-gas-induced acceleration of the rate of sea level rise is now widely accepted by the international scientific community. The Intergovernmental Panel on Climate Change Working Group I projects a rise in global sea level of 0.3 to 1.1 meters by the year 2100, with a "best estimate" of .66 meters (IPCC, WG1, 1990). A 1-meter global eustatic rise is increasingly used for assessing, planning, and managing the impacts of sea level rise (IPCC, CZMS, 1990; Dennis et al., 1992). Whereas sea level rise is widely regarded as the most important and most knowable consequence of climate change (Hekstra, 1989), in-depth scientific analyses of the socioeconomic and environmental impacts associated with sea level rise have been completed in very few countries. Global assessments of the impacts of sea level rise and the costs of protecting against those impacts have been undertaken, and response strategies and comprehensive coastal zone management planning are being considered for universal application without the benefit of even the most basic information from the majority of the nations at risk (IPCC, CZMS, 1990).

Mounting evidence reveals an ever greater burden of impacts related to sea level rise being borne by the developing world (ASPEI, 1988; UNEP, 1989; Jacobson, 1990; Dennis et al., 1991; Psuty and Jogoo, 1991; Devine, 1992), where the barriers to implementing mitigation strategies (structural and planning) are the greatest (Sorensen, 1987; Roy and Connell, 1988; Ibe et al., 1989;

Massei, 1990; Wije and Adikaramge, 1991; Daniel, 1992). In its effort to address the global dimensions of the problem, the IPCC's Coastal Zone Management Subgroup (1990) identified the following as high priorities:

- Identifying coastal areas at risk.
- Providing technical assistance for developing nations in assessing vulnerability.
- Implementing comprehensive coastal zone management plans.

Currently a number of case studies are being carried out, in cooperation with IPCC member states and/or the United Nations Environment Programme (UNEP). These studies are using a "common methodology" toward assessing the vulnerability of a variety of developing nations to the impacts of sea level rise (NOS, 1992).

This paper reports on a low-cost, complementary international effort, supported through Rutgers—The State University of New Jersey by the U.S. Environmental Protection Agency. This effort involves selected developing countries that are using a similar methodology for obtaining comprehensive assessments of the impacts of sea level rise. The resulting data sets produced in their reports and their interpretation within national social and economic contexts have important implications for current international scientific, managerial, and policy efforts with respect to sea level rise.

INTERNATIONAL SEA LEVEL RISE STUDIES PROJECT

The International Sea Level Rise Studies Project is an effort to identify and quantify resources at risk to a greenhouse-accelerated rise in sea level in developing countries. Initiated in 1989, the first phase of the project employed local scientists in 18 countries (Figure 1). Reports included:

- Description of the physical characteristics, processes, and hazards of the coastal zone.
- Identification of the resources at risk.
- Discussion of the range of institutions and response strategies available to mitigate the threat of sea level rise.

In addition to incorporating estimates of the resources and populations at risk, initial reports contain a host of ancillary data relevant to understanding potential risk in certain nations and regions. The data include wave climatology, coastal geomorphology, shoreline erosion rates, and storm surge. A few of the reports contain tabulations of aspects of land use in the low-lying coastal zone.

A second phase of the project was initiated with 11 countries in 1990 to improve conceptualization of the scope and the magnitude of the impacts related to sea level rise (Figure 1). This was accomplished through a comprehensive enumeration of features at risk. The primary objective of the National Assessments of Risk (Phase II) was to provide basic quantitative measurements of features at risk to accelerated sea level rise. Specifically, the project entails:

- Multidimensional enumeration of natural and cultural features at risk in the intertidal and 0.0 to 2.0-meter zones.
- Construction of spreadsheets to allow interpretation of data at the local, regional, and national scales.

- Concluding from tabulations and existing knowledge of the national significance of sea level rise and the needs and opportunities or limitations of response.
- Relation of the data to broader questions of science and national policies.

FIGURE 1. MAJOR THEMES AND THE PARTICIPATING COUNTRIES IN THE INTERNATIONAL SEA LEVEL RISE STUDIES PROJECT, PHASES I AND II (1989-1992)

PHASE I: National Assessments: Impacts and Potential Responses to Sea Level Rise

- Coastal Geomorphology
- Preliminary Assessments of Sea Level Rise Impacts
- Potential Responses/ Institutional Capacity

Central and South America	Europe	Africa	Asia/Oceania
Argentina	Greece	Benin/	China
Chile	Poland	Togo	Malaysia
Eastern Caribbean	Portugal	Tunisia	Sri Lanka
Guyana	Turkey	Mauritius	Papua New Guinea
Mexico	Ukraine		
Venezuela			

PHASE II National Assessments:
Quantification of Natural, Cultural, and Economic Features at Risk

- Linear and Areal Measurements of Features at Risk
- Economic Value of Features at Risk
- Implications for Science, Management, and Policy

Central and South America	Europe	Africa	Asia
Chile	Poland	Benin	Sri Lanka
Eastern Caribbean	Portugal	Tunisia	
Guyana		Mauritius	
Mexico			
Venezuela			

This paper presents the methodology developed to quantify the elements at risk, interprets some of the data that are being generated by the national contacts, and concludes by identifying some of the implications of this research for sea level rise science and management.

METHODOLOGY FOR CONDUCTING THE NATIONAL ASSESSMENTS OF RISK

The National Assessments of Risk were initiated before the IPCC established its "common methodology" (IPCC, RSWG, 1991), and with limited financial support for each country.

Certainly, a uniform methodology is desirable and necessary if the national outputs are to be compared and evaluated. The 11 countries and regions participating in Phase II contributed to the development of the methodology applied to the collation of information (Figure 2). This intricate data matrix groups features at risk into two zones and includes linear and areal features and enumeration, economic value, production, and, where possible, the percentage of the national totals present in these zones.

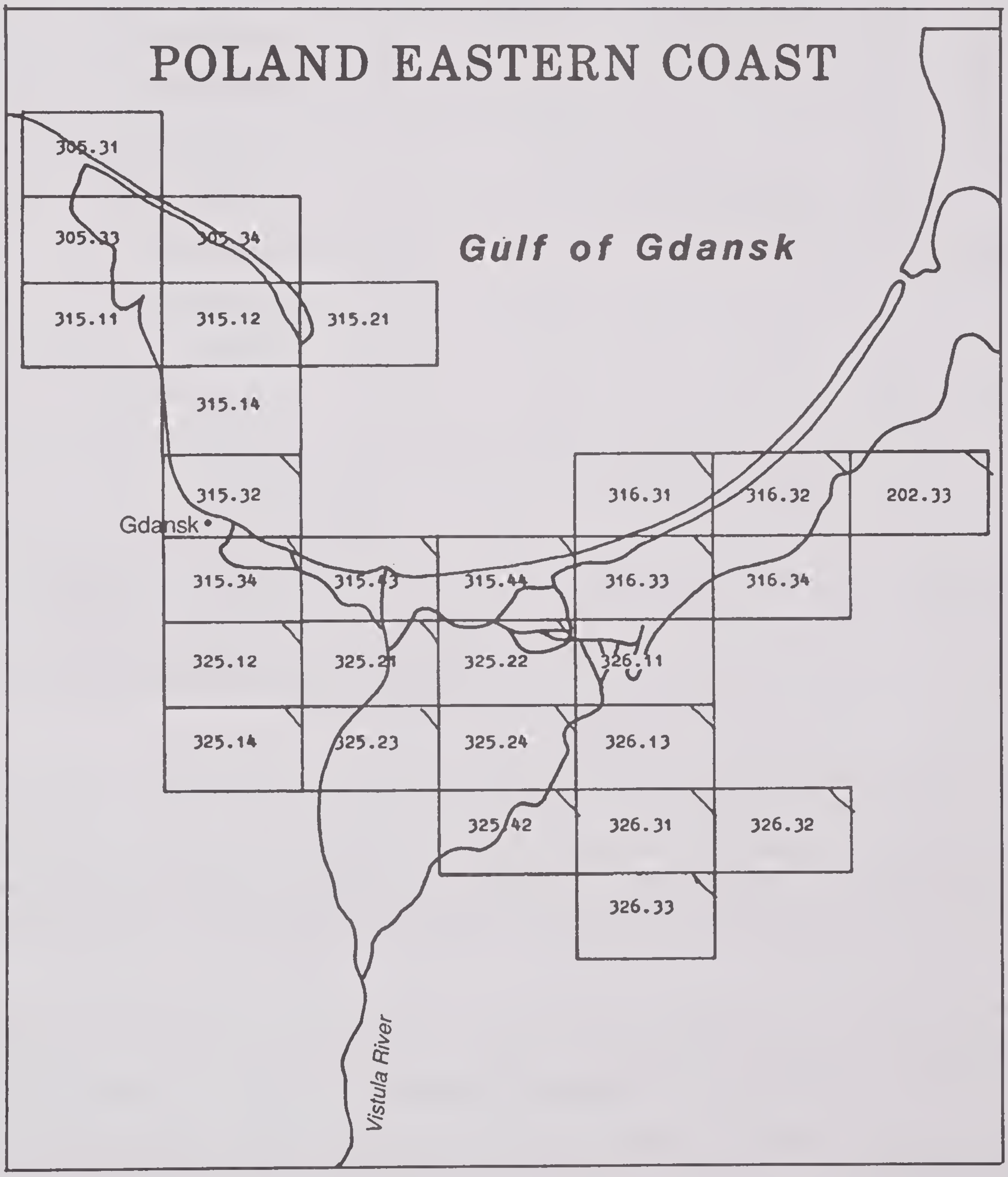
FIGURE 2. INTERNATIONAL SEA LEVEL RISE STUDIES PROJECT RISK QUANTIFICATION DATA MATRIX

Type of Measurement Required	**Zone I** (intertidal zone)	**Zone II** (0-2m above high tide)
LINEAR (length of feature)	Natural Features Marsh/mud (tidal) flat Mangrove/swamp Coral reef Beaches (with/without dunes) Cliffs/rock platforms Cultural Features Seawalls, jetties, bunds Bridges Dikes/Canals	Natural Features Cliffs Dunes Cultural Features Bridges/roads/rail lines Harbor frontage Commercial/industrial frontage Tourist resort frontage Residential frontage
AREAL	Natural Features Marsh Mangrove Mud flat Cultural/Economic Features Pasture (diked and undiked) Agriculture (rice, sugar, mixed,etc) Aquaculture Industry (limekilns, salt pans, etc.) Parks/Recreation Settlement	Natural Features Forest/scrub Grassland/savannah Settlement Types Urban/rural distinctions Residential, informal settlement Agricultural/fishing Resorts/tourism Cultural/Economic Features Pasture (diked and undiked) Agriculture/aquaculture Industrial/commercial Parks/recreation, historical, etc Harbor facilities, docks
QUANTITIES	Cultural Features Bridges (# affected) Farms (fish and crop) Groins/jetties or other infrastructure	Population Urban/rural/informal settlement Farms/fishing centers, etc. Economic Features Ports/airports/marinas Industrial/commercial sites Tourism (# of resorts/rooms etc) Harbor statistics, air traffic
WEIGHT	Economic Production Agricultural Fishing Industrial	Economic Production Agricultural Fishing Industrial
VALUE (in US $)	Economic Production Agricultural Fishing Industrial Other Structural protection (seawall, etc) Harbor facilities	Economic Production Agricultural Fishing Industrial Tourism Other Residential Commercial

For the most part, the country contacts are independent university scientists with first-hand knowledge of the coastal zone by virtue of their training, experience, and specialization in aspects of coastal inquiry. Their personal experiences in collection of the data contributed to successive revisions of the matrix.

To quantify uses and features in the coastal zone, most researchers used the largest-scale topographic maps available. There is considerable art in this method since these maps generally do not delineate the 2-meter contour. Thus, the experts had to use their knowledge and other resources to interpolate the position of the high-tide line and the position of the 2-meter contour above high tide. Data were accumulated and tabulated for each topographic sheet, which became a data cell, as illustrated by the grid pattern for the eastern coast of Poland (Figure 3). Maps were augmented by aerial photographs, published literature, personal knowledge, and field checks.

FIGURE 3. AN EXAMPLE OF THE SPATIAL MATRIX OF POLISH TOPOGRAPHIC MAPS USED IN COMPILING MAGNITUDES OF COASTAL RESOURCES AT RISK



Source: Rotnicki and Borowka, 1992.

Once the individual maps were tabulated, the matrix cells could be summed to present regional or national totals. Table 1 illustrates the areal measurements for one topographic sheet in Sri Lanka, and Table 2 presents the cumulative areal measurements for the 36 maps (1:63,360 scale) that were analyzed for the Sri Lankan National Assessment of Risk report.

TABLE 1. COASTAL LAND USE/LAND COVER IN PUTTALAM, SRI LANKA

Measurement	**Intertidal Zone**		**0-2 m above high tide**	
AREAL hectares	natural		natural	
	mangrove	137.2	marsh	733.0
	marsh	82.9	scrub	686.4
	salt marsh-mangrove	77.7	forest/jungle	321.2
			sandy scrub	235.7
			other lands	688.9
	cultural/economic		cultural/economic	
	settlement	5.2	agriculture	1,138.6
			settlement	603.5
			commercial	132.0
			salterns	130.1
			village gardens	33.7

Source: Wije and Adi Karamge, 1992.

Before proceeding with the presentation and interpretation of data, it is important to explain the use of Zones I and II in the data matrix. At the time of the first project, the international community was using 0.5-, 1.0-, and 2.0-meter elevations to develop scenarios of the impacts of sea level rise. Although estimates of global eustatic sea level rise have since been revised downward, the 2.0-meter contour was retained for several reasons:

- Ongoing research initiatives were based on use of the 2.0-meter contour.
- It is necessary to acknowledge and address the issue of coastal subsidence in addition to sea level rise. Local subsidence is an important consideration, whether it is a result of tectonics, sediment compaction, or overpumping of ground water. Its displacement is frequently as great as or greater than the magnitude of absolute sea level rise.
- With a rise of sea level, there will be greater penetration of storm water with an accompanying increased exposure of features in the coastal zone, so that the areas at risk will extend beyond the arithmetic elevation of the water level.
- It is extremely difficult to identify categories of land use within very small intervals of elevation.

Despite the difficulties inherent in the spatial separation of coastal resources and land uses into narrow vertical zones, scientists have identified one grouping that spans the intertidal region and another that occupies the zone immediately above high tide. Therefore, data are tabulated for the categories (1) intertidal and (2) 0.0 to 2.0 meters above high tide. This approach emphasizes the significance of land uses distributed along vertical coastal environmental gradients and ties the vertical and horizontal components together.

TABLE 2. COASTAL LAND USE/LAND COVER IN SRI LANKA

Measurement	Intertidal Zone		0-2 m above high tide	
AREAL hectares	natural		natural	
	salt marsh mangrove	2,934.7	marsh	9,770.9
	marsh	1,297.3	scrub	8,557.4
	beach	993.6	forest/jungle	6,335.0
	mangrove	829.5	sandy scrub	432.5
	scrub	25.9	other lands	228.3
	coral	20.7		
	cultural/economic		cultural/economic	
	agriculture	95.8	agriculture	28,853.8
	settlement	80.3	settlement	9,499.0
	salterns	46.6	salt pans	2,147.1
	industry	10.3	palmyra	1,872.6
	village gardens	2.6	village gardens	749.9
			tourism	31.3

Source: Wije and Adikaramge, 1992.

SELECTED NATIONAL ASSESSMENTS

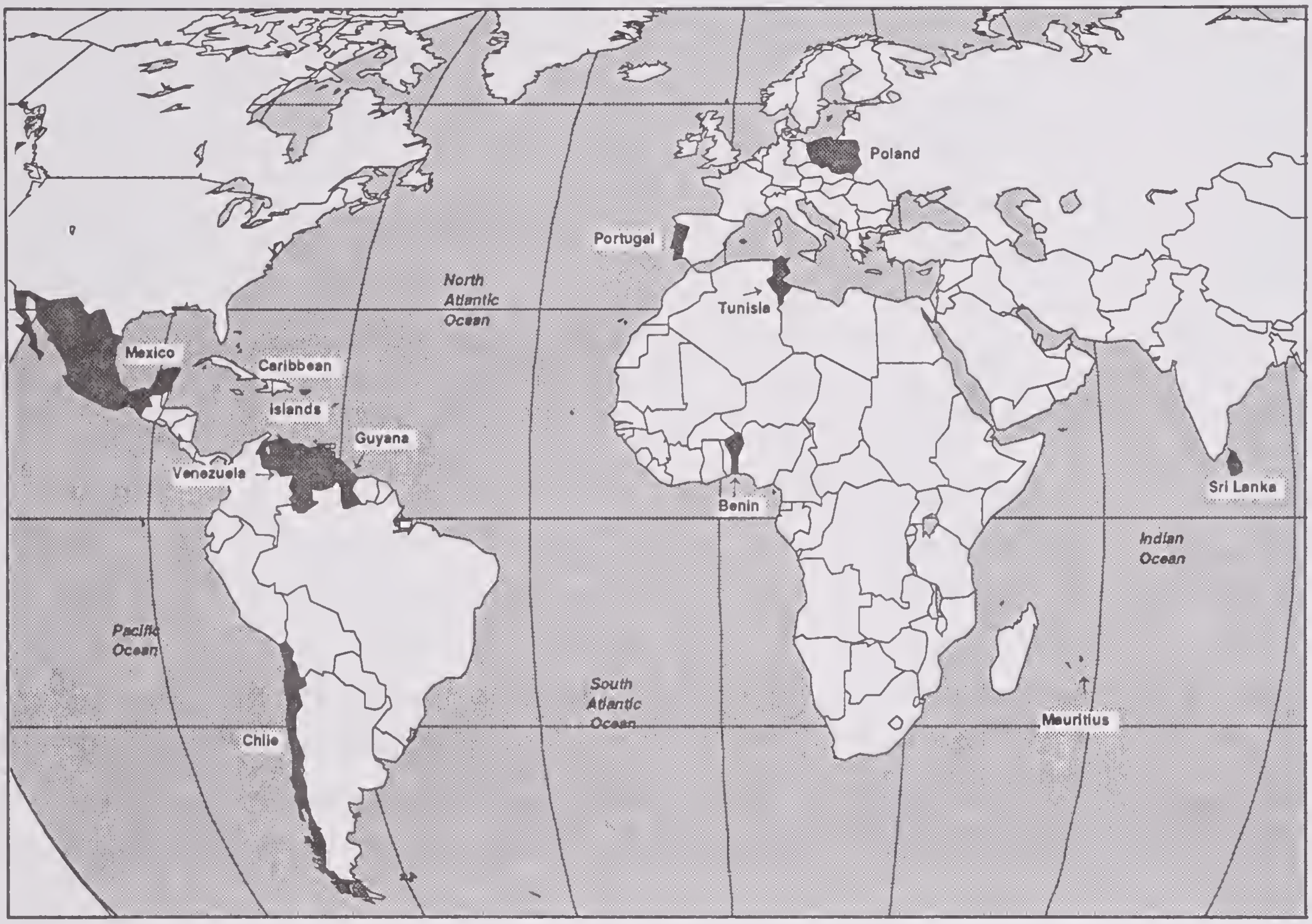
Data from 6 of the 11 National Assessments of Risk illustrate the variety of information gathered and its implications for a diversity of environments, cultures, and levels of economic development at risk. The examples emphasize interpretation of data in the ongoing socioeconomic context and thus not only seek to improve empirical understanding of the dimensions of the sea level rise dilemma for developing nations, but also represent an effort to inform international research, management, and policy related to sea level rise.

BENIN

IMPACTS ON URBAN CULTURE AND THE NATIONAL ECONOMY

A large and increasing proportion of Benin's urbanization and economic activity is concentrated along this small island country's barrier beaches (Figure 4). The 125-km coastline in western sub-Saharan Africa is characterized by a series of barrier islands and is backed by narrow lagoons. The barrier islands rarely include land above 3 meters in elevation, and most settlements and economic activities would be at risk to the early stages of accelerated sea level rise. A 1.0-meter rise in sea level would seriously threaten the country's largest towns and nearly all major economic and infrastructural investment. For example, two-thirds of the area of Cotonou, the capital city, would be inundated (Adam, 1991).

FIGURE 4. LOCATION OF COUNTRIES WHERE NATIONAL ASSESSMENTS OF RISK WERE CONDUCTED



The linear and areal measurements in Table 3 describe the land cover and land uses in the barrier environment. Whereas in a numerical sense the totals are quite modest, they represent very serious dislocations for Benin at the national scale. For instance, located within 2 meters of high tide are 15 percent of the country's total urban settlements, 50 percent of its tourist accommodations, 75 percent of its industrial production capacity, and all of its airport facilities. Dislocations to the port of Cotonou would be of paramount concern because of the increasingly dominant role the port plays in the economic development of the country (Adam, 1991).

TABLE 3. LAND USE, LAND COVER, AND ACTIVITIES AT RISK TO SEA LEVEL RISE IN THE BARRIER BEACH ENVIRONMENT OF BENIN

Measurement	0-2 m above high tide		
Linear (km)	natural features		
	beaches with dunes	125	
	cultural/economic features		
	bridges	135	
	roads	32	
	rail lines	1	
Areal (hectare)	natural features		
	marsh	31,800	
	savannah/grassland	7,800	
	lagoon	2,400	
	marshy forest	2,000	
	mangrove	1,370	
	cultural/economic features		
	plantation	7,740	
	urban/industrial	6,410	
	cultivated and fallow	1,250	
	rural	700	
Quantity	population	880,000	(17.5% of national total)
	urban	750,000	(15% of national total)
	rural	130,000	(2.5% of national total)
	tourism		
	beds	1,250	(50% of national total)
	rooms	800	(50% of national total)
	air traffic		
	flights	6,300	(100% of national total)
	passengers	115,800	(100% of national total)
Value (US dollars)	agricultural production	$11,500,000	(5.8% of national total)
	industrial production	$200,000,000	(75% of national total)

Source: Adam, 1992.

POTENTIAL FOR RESPONSE

The barrier islands in Benin are already experiencing intensive development and erosion. Erosion related to sea level rise and beach profile adjustment will accelerate the narrowing and retreat of the barriers. Urban, industrial, and agricultural development, including the expansion of Cotonou onto ever lower elevations, will not have the possibility of retreat. Currently, protecting the littoral zone with naturally occurring beach rock is the preferred response method, but its effectiveness will rapidly decrease under any acceleration of sea level rise (Adam, 1991).

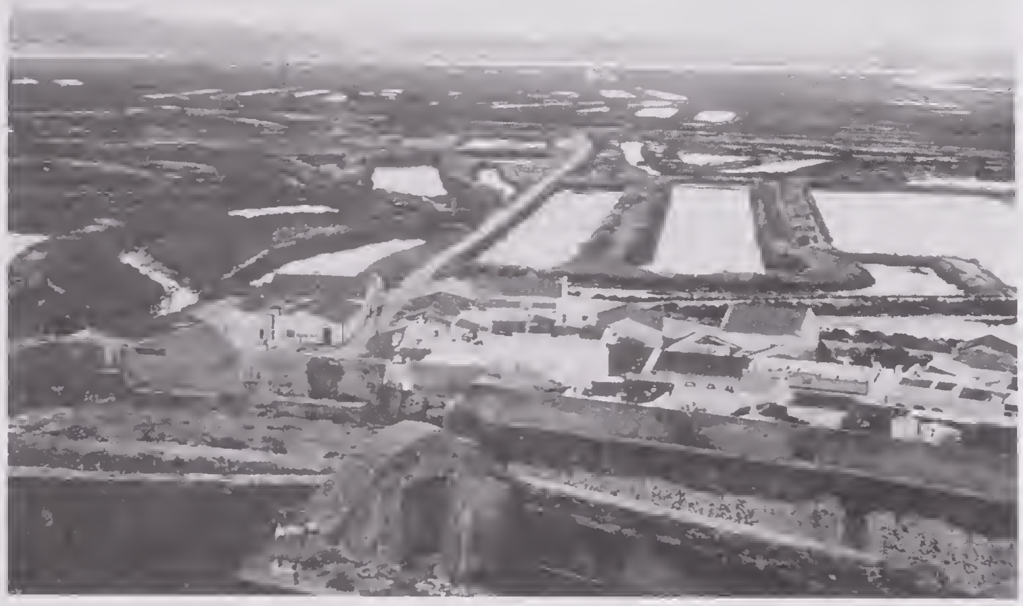
Among the hypothetical response options to the early stages of accelerated sea level rise, structural protection of the developed areas on the barrier islands would involve very high and recurring costs, whereas relocating economic infrastructure and settlements inland (to a very different environmental setting) would involve a massive economic burden and a complete loss of current modes of life for a significant proportion of the Beninian population. Either of these options is a daunting prospect. No type of protective measure will be feasible in this environment under a 1.0-meter rise in sea level (Adam, 1991). In light of the apparent inability to prevent the impending cultural and economic catastrophe related to accelerated sea level rise, it would seem appropriate to restrict further development on the barrier systems. Yet port construction, urbanization, and tourist developments continue unabated. Concern about coastal land use has not moved beyond academic reflection, and the government has not even begun to consider coastal management ideas (Adam, 1991).

PORTUGAL

RISK TO INTENSIVELY DEVELOPED ESTUARINE SYSTEMS

The recent research of Moreira (1992) illustrates the risk of rising sea levels on developed estuarine systems. Of the 870 km of shoreline in Portugal, about one-third is considered part of an estuarine system. The growth of the most important towns, harbors, and industries in Portugal extends over reclaimed estuarine areas and lagoonal margins. More than 90 percent of Portugal's wetlands have been altered for multiple uses to drive economic development (Figure 5).

FIGURE 5. AGRICULTURAL LAND IN GUARDIANA ESTUARY, PORTUGAL



Agricultural land has largely replaced the natural wetlands in the estuarine systems of Portugal.

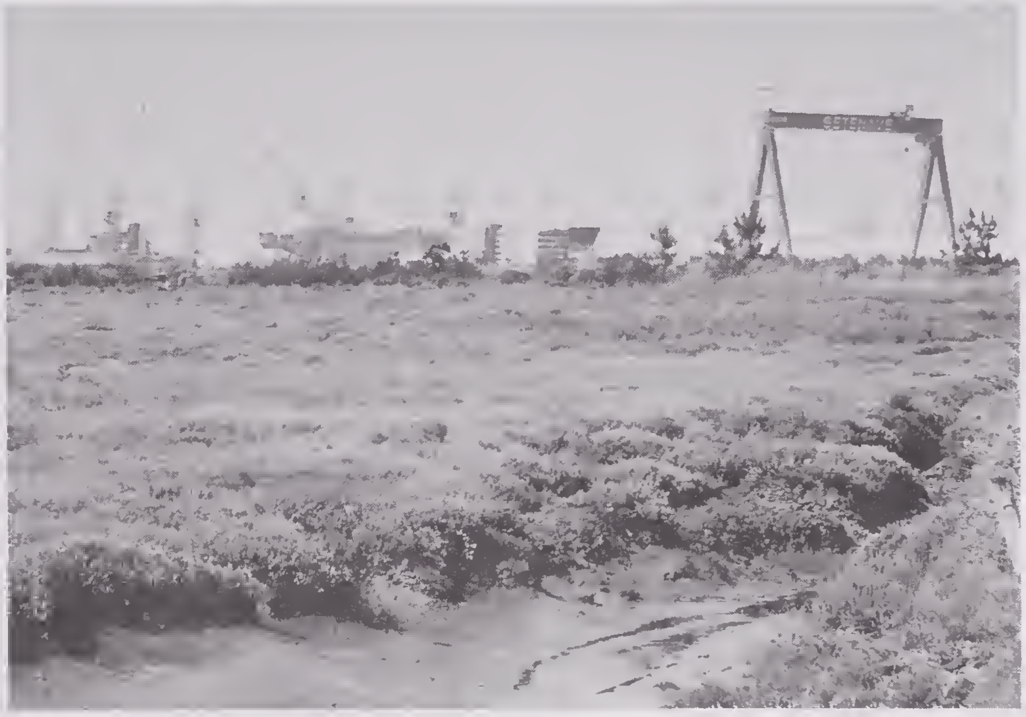
Lisbon, the capital of Portugal, is located in one major estuary. Another vital estuary—the Sado estuary—is directly to the south. It contains one of the few remaining natural estuarine environments in the country. Although part of the estuary has national park status, a large part has been designated for development, including heavy industry, chemical production, cement, salt ponds, agriculture, pasture, and aquaculture ponds, all located within the intertidal zone or just above it (Figure 6) (Moreira, 1992). The measurements in Table 4 are based on eight 1:25,000-scale topographic sheets covering the Sado estuarine area. The data show that half of the intertidal area has already been altered. As is the case in many estuarine areas, land-use activities are often at high-tide level, or below dikes that are barely above spring-tide levels (Figure 7).

TABLE 4. LAND USE/LAND COVER IN SADO ESTUARY, PORTUGAL

Measurement	**Intertidal Zone**		**0-2 m above high tide**	
Linear km.	natural features		natural features	
	beaches	26.4	cliffs	10.3
	dune beaches	26.5	dunes	38.0
	cliffs	8.1		
	rock platforms	6.6	cultural/economic features	
	cultural/economic features		bridges	.4
	dikes	115.7	roads	15.6
	canals	57.6	rail lines	11.5
Areal hectares	natural features		cultural/economic features	
	mudflat	3,671.3	agriculture	470.1
	marsh	1,427.9	industry	10.4
			pasture	83.6
	cultural/economic features		docks	100.1
	agriculture	3,127.1	urban	29.6
	industry	950.3	residential	12.8
	pasture	258.8	resorts	12.7
	aquaculture	131.3	parks/recreation	4.7

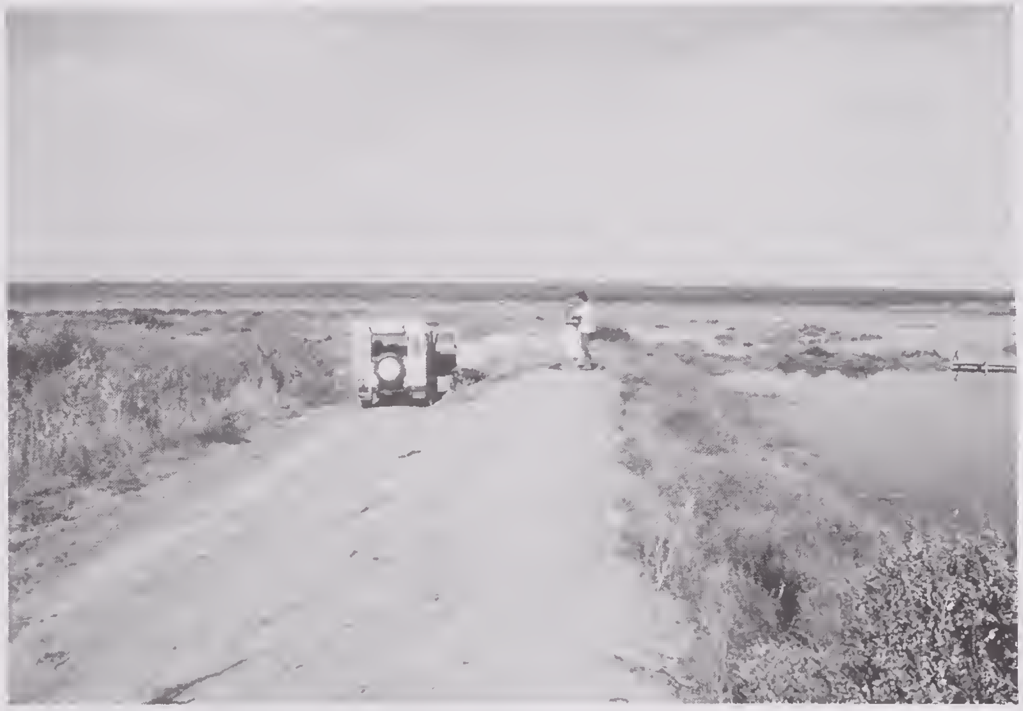
Source: Moreira, 1992.

FIGURE 6. SHIPYARD DEVELOPMENT IN PORTUGAL'S SADO ESTUARY



Another example of intertidal land use is shipyard development replacing high-tide wetlands in Setenave, Sado Estuary, Portugal.

FIGURE 7. SPRING HIGH TIDES IN PORTUGAL'S SADO ESTUARY



Spring high tides nearly reach the top of existing dikes around pasture and agricultural lands in Portugal's Sado Estuary.

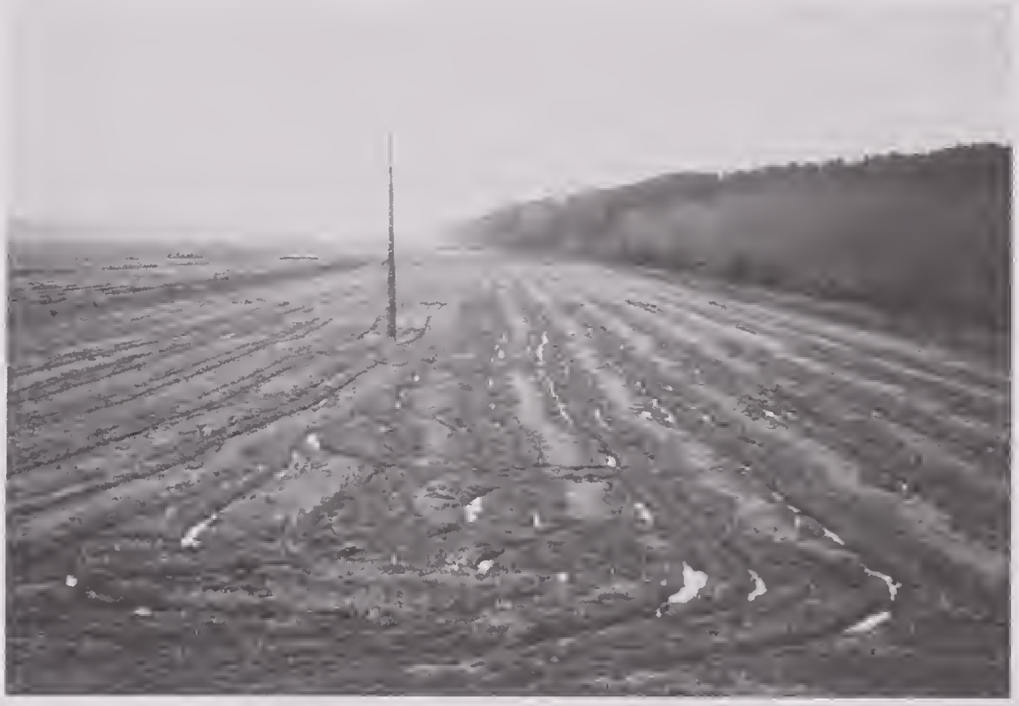
The most important aspect of the data set is that development in estuarine areas is concentrated within the intertidal zone itself, rather than on adjacent higher elevations. Thus, even the very early stages of sea level rise will result in the accelerated erosion and submergence of developed shorelines in intertidal environments, with considerable economic impacts. For Portugal, accelerated sea level rise in estuarine areas represents threats to:

- Present land uses and levels of development.
- Efforts to preserve a part of the natural system.
- Large industrial investments.
- Future economic development plans.

POTENTIAL FOR RESPONSE

Because the sides of the Sado Estuary are steep (Figure 8), there is really no zone for many of the land uses or natural systems to easily migrate. Because reclamation causes stabilization of the ecosystem, migration of the salt marsh is not possible. Most activities must either be defended in place or abandoned. Simple relocation is not a possibility for many of the industries and occupations because they exist in association with estuarine dynamics and ecologies.

FIGURE 8. SLOPES ALONG THE SADO ESTUARY



Steep slopes along the margin of the Sado Estuary will prevent the horizontal displacement of the natural ecosystem.

Responses to an accelerated sea level rise will need to be different from current responses to erosion (Moreira, 1991). For instance, many impacts in estuarine areas related to sea level rise cannot be mitigated simply by strengthening existing protection measures (current structural protection of some salt works and urban areas is already insufficient).

Urban, industrial, and port areas represent the highest investments on the reclaimed areas. Although much of their infrastructure is well above sea level and protected against storm waves, fluvial flooding in association with storm surge very often results in substantial inundation. Sea level rise will exacerbate these conditions. Moreover, the estuarine area itself will extend inland, penetrating the fluvial system and causing salinization of estuarine aquifers, fluvial plains, and reclaimed lowlands. Response to salinization and inundation will necessitate increasingly complex and expensive structural measures, technological changes, or a wholesale shift in the type of land use in the reclaimed areas (Moreira, 1991).

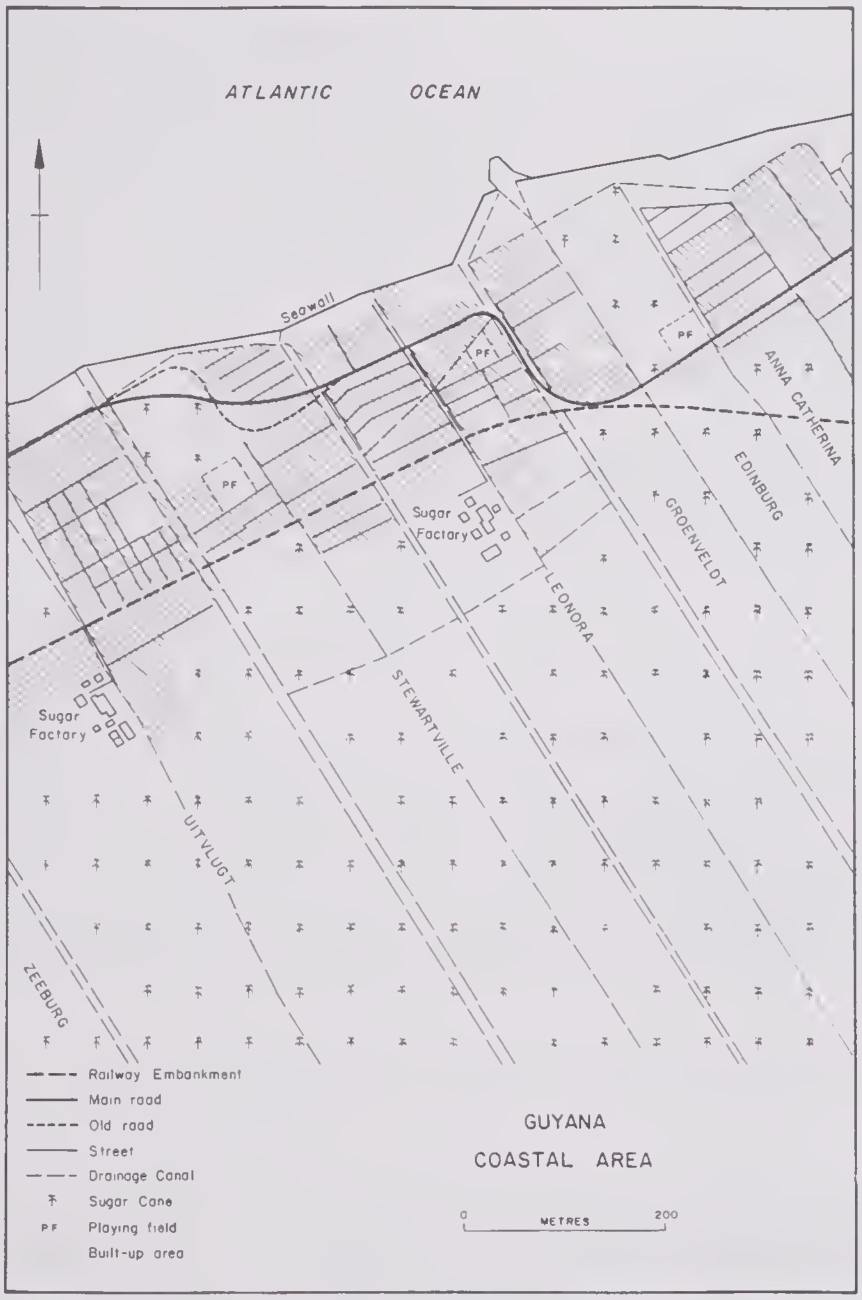
An important obstacle to the management of sea level rise in Portugal will be the frequent disagreement among the national, regional, and local entities and private owners, with respect to environmental concerns. Preventive measures and land-use changes are not yet part of the planning process. Proposals to decrease development pressure on the coastal fringe will be accepted with great difficulty (Moreira, 1991).

GUYANA

CULTURAL DEPENDENCE ON LAND USE WITHIN INTERTIDAL ZONES

Guyana is representative of a number of countries where nearly all settlement and economic activities are located in and depend on a low, flat, coastal plain environment. Guyana's 500-km shoreline fronts an extremely low coastal plain (several meters high and 5-12 km wide), characterized by a series of shore parallel ridges (referred to as *cheniers*) interspersed with wetlands at the intertidal level. Ninety percent of the Guyanese population and the vast majority of economic investment (e.g., agriculture, fishing, cattle farming) are concentrated in this coastal belt (Daniel, 1991). Habitation and infrastructure exist on the 2- to 3-meter-high chenier ridges, whereas the agriculture and extractive industries are within the intervening swales (Figure 9).

FIGURE 9. LAND USE IN THE COASTAL ZONE OF GUYANA RELATED TO THE CHENIER TOPOGRAPHY



Source: Daniel, 1991.

The data in Table 5 represent the areal measurement totals for all intertidal areas in Guyana. These data, assembled on the basis of 39 topographic sheets (1:50,000 scale), reveal the vast extent of intertidal areas and the natural and agricultural systems they support. Eighty-four percent of the national total cultivated land is within the intertidal environment. Intertidal agricultural production contributes nearly 50 percent of the gross domestic product (Daniel, 1991). The sugarcane and rice industries, located exclusively on the coastal plain, employ the largest labor force in the country. Because of the extent to which Guyanese society has evolved in close association with current and past sea levels, an accelerated sea level rise of any magnitude will have serious cultural and economic consequences for Guyana's coast and the country as a whole.

TABLE 5. LAND USE/LAND COVER IN THE GUYANA INTERTIDAL ZONE

Measurement	**Intertidal Zone**	
Areal (hectare)	natural features	
	swamp	471,830
	marsh	117,820
	forest	89,220
	mangrove	2,690
	shell beach	110
	agriculture	
	rice	96,020
	sugar	60,380
	coconut	31,370
	mixed farming	16,180
	market gardening	280
	settlement	24,818

Source: Daniel, 1992.

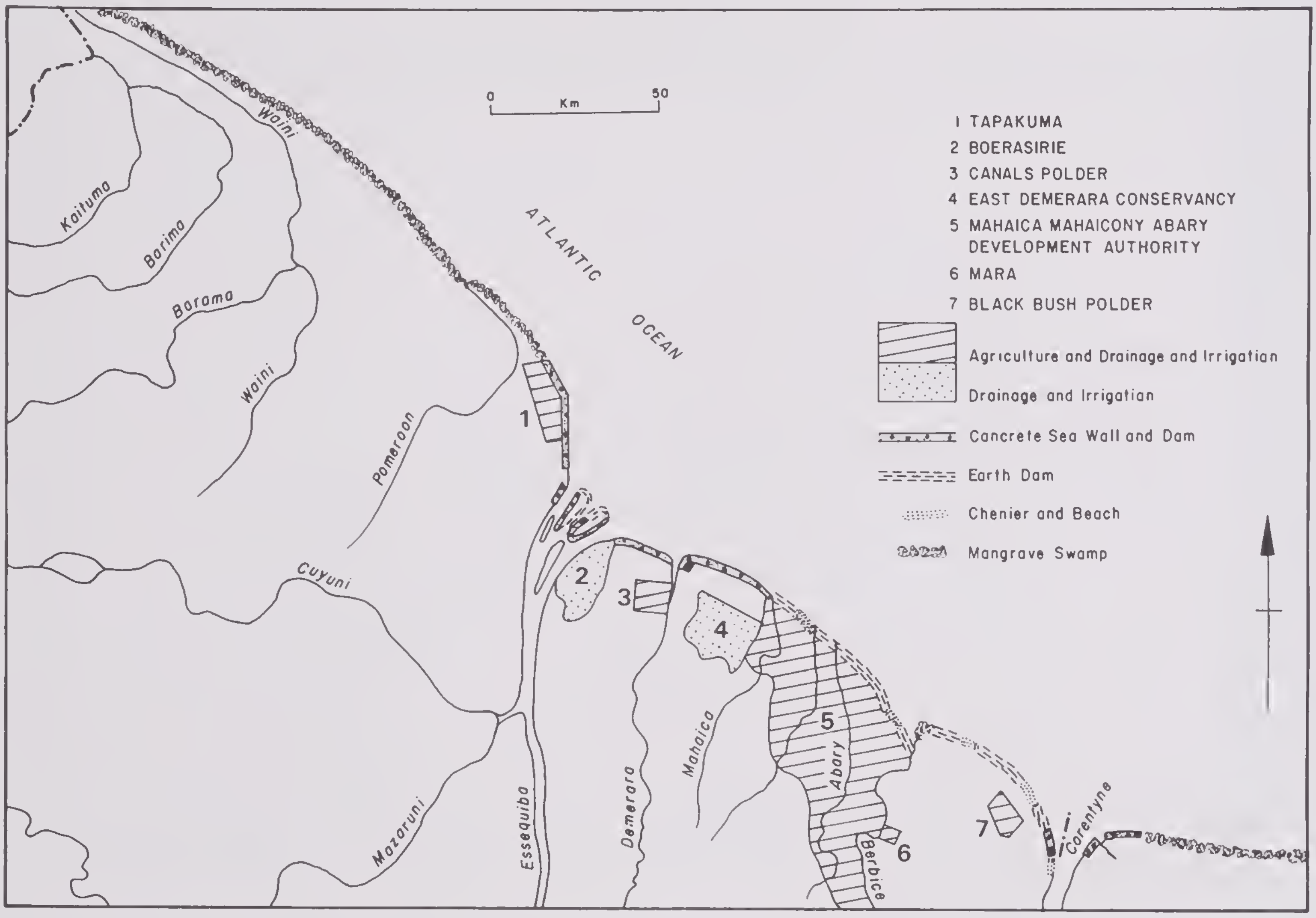
As in the Sado Estuary case, a large proportion of the economic investment of Guyana is essentially in intertidal areas. In this kind of setting, coastal defense structures and water management are major areas of concern (Figure 10). Since the 1940's, 30–40 percent of the total expenditures allocated for national development have been used for drainage, irrigation, and sea defense works (Daniel, 1992). Most of the coast and river banks are protected by earth embankments. Types and lengths of sea defense are shown in Table 6. Figures 11 and 12 are illustrative of coastal protection infrastructure in Guyana.

TABLE 6. TYPES AND LENGTHS OF SEA DEFENSE ON THE COAST OF GUYANA

	Earth Dams			
Reefs (cheniers)	With toe protection	Without toe protection	Seawalls	Total
120.7	239.8	10.3	159.3	530.1

Source: Daniel, 1988.

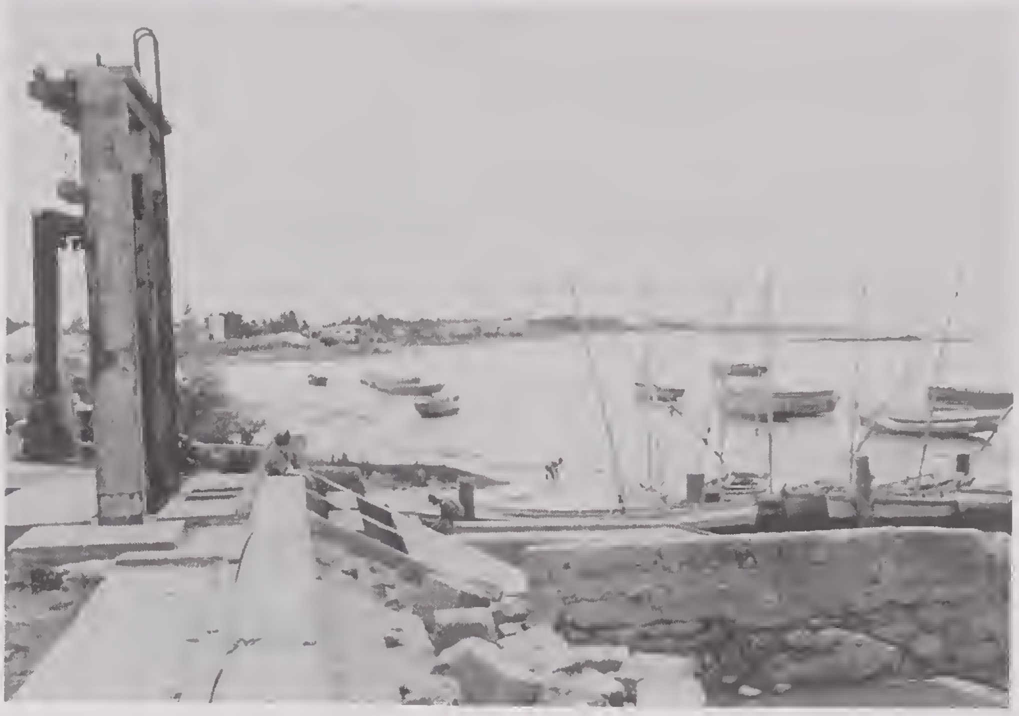
FIGURE 10. DISTRIBUTION OF COASTAL PROTECTION AND LAND DEVELOPMENT PROGRAMS ALONG PART OF THE COAST OF GUYANA



Source: Daniel, 1991.

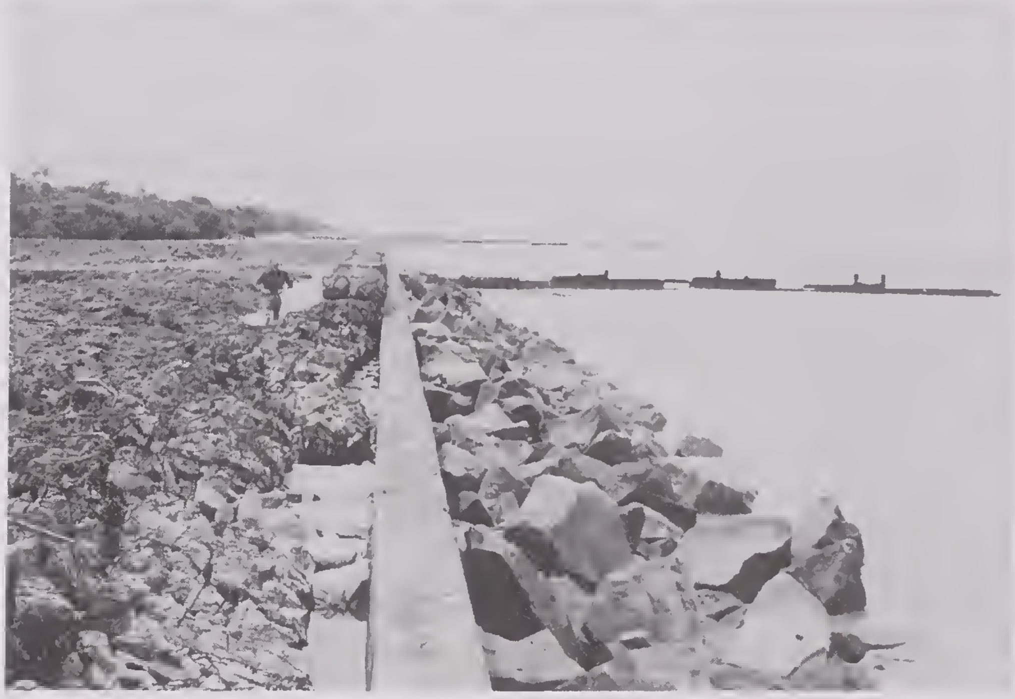
Massive increases in investments for structural protection will be necessary under any sea level rise scenario because of the delicate balance struck by natural systems, structural defense, and economic production. For instance, studies have shown that if sea level rises by 0.3 meters, the frequency of overtopping of sea walls would increase threefold (Daniel, 1991). A sea level rise of 0.5 meters would not only accelerate erosion of the sea walls, but it also would cause flooding and saltwater intrusion into the valuable agricultural land. Proposed future development of the coastal plain (e.g., expansion of agricultural practices) will largely depend on maintenance and extension of the coastal defense system. Accelerated sea level rise will make this very difficult to achieve.

FIGURE 11. COASTAL PROTECTION IN GUYANA



Source: (Daniel, 1991).

FIGURE 12. DETERIORATED DIKES IN GUYANA



Deterioration of dikes, which protect coastal infrastructure, is now common in Guyana (Daniel, 1991).

POTENTIAL FOR RESPONSE

Despite Guyana's lengthy experience with battling the sea, as well as ongoing access to international consultants, technology, and aid, the sea defense system in urban and agricultural areas is insufficient and is deteriorating due to internal economic constraints as well as lack of political commitment (Daniel, 1992). For example, in just three months during 1985, as many as

37 breaches were reported along a 5-km stretch of sea wall near the Corentyne River (Daniel, 1988). A summary of recent major sea breaches (Table 7) corroborates the limited capacity for effective response. Under current rates of sea level rise and current economic constraints, valuable agricultural land is already being abandoned. Even the early stages of accelerated sea level rise will present significant problems for all portions of the coast that are now protected.

TABLE 7. RECENT BREACHES OF THE SEA DEFENSE SYSTEM OF GUYANA

Area	Wakenaam (1989, 1990, and 1991).
Stretch	Several breaches along a 750-m stretch.
Action	Farmers took individual action.
Result	Ineffective, many farmlands abandoned.
Area	Parika (1989).
Stretch	Several breaches along a 75-m stretch of sea wall.
Action	Farmers took individual action.
Result	Ineffective, low-lying areas inundated during high tide. Farmlands abandoned.
Area	Clonbrook (1989–90).
Stretch	A 152-m stretch of sea wall collapsed when its foundation sank.
Action	Earth embankments (sand crete, sand bags and boulders) constructed behind, and timber revetment erected in front of, collapsed sea wall. Flooded area drained.
Result	Saltwater intrusion of farmlands. Mixed farming affected. Erosion mostly contained.
Area	63rd Village (1989).
Stretch	90 m of earth embankment destroyed.
Action	Embankment rebuilt with adjacent sands and fortified with scrap iron and tree limbs.
Result	Ineffective, most of the coconut plantations destroyed.
Area	Skeldon (ongoing).
Stretch	Stress fractures along an 800-m stretch of sea wall.
Action	Some owners of dwellings have raised floors above the high tide level.
Result	Worsening situation; settlements inundated during high tide, roadbed failing, many buildings threatened.
Area	Crabwood Creek (1989, 1990).
Stretch	Earth embankments along a 61-m stretch destroyed.
Action	Timber revetment constructed.
Result	Erosion partially contained. Mixed farming near coastline affected.

Source: Daniel, 1992.

An effective response to sea level rise in Guyana will be possible only if significant progress is made with respect to current economic and institutional barriers. Economic constraints have forced Guyana to adopt an "emergency maintenance and repair" approach to sea defense, rather than a comprehensive management response. Even this level of management has encountered "innumerable difficulties," such as lack of foreign exchange for machinery and equipment; inadequate monitoring, reporting, mapping, and geomorphological research; lack of trained personnel; and limited access to sea walls. In addition, two international consulting teams contracted to provide advice related to shoreline management have developed divergent perceptions of Guyana's coastal problems and have suggested conflicting strategies (Daniel, 1991).

POLAND

POTENTIAL RISKS TO AN AGRO-INDUSTRIAL ECONOMY

The work of Rotnicki and Borowka (1992) in Poland has provided data on risks related to sea level rise in intensively urbanized, cultivated, and industrialized estuarine, deltaic, and lower river valley environments. The Polish shoreline extends for about 500 km, and the low-lying coastal zone supports vast tracts of agriculture and several major urban/industrial areas.

Data in Table 8, derived from 87 sheets of the Topographic Map of Poland (1:25,000 scale), provide totals of the areal measurements of natural and cultural features in the Polish coastal zone. Thirty percent of the Polish coastal zone below 2.5 meters is cultivated, 28 percent is in pasture, and almost 12 percent has been settled (including urban, rural, and resort areas). Most striking is the finding that nearly 87 percent of the intertidal area has been developed.

TABLE 8. POLAND: LAND USE/LAND COVER IN AN AGRO-INDUSTRIAL ECONOMY

		Intertidal	**0 - 2.5 m**	**Total**
AREAL ha	natural			
	wet meadow	5,799.0 (9.0%)	42,729.8 (20.8%)	48,288.8 (18.0%)
	forest	2,427.2 (3.8%)	18,478.3 (9.0%)	20,905.5 (7.8%)
	lakes/rivers	313.0 (0.5%)	31,419.3 (15.3%)	31,732.3 (11.8%)
	cultural/economic			
	cultivated field	27,966.7 (43.7%)	53,181.1 (25.9%)	81,184.6 (30.1%)
	pasture	27,041.1 (42.1%)	50,164.1 (24.4%)	77,205.2 (28.6%)
	urban/industrial	550.8 (0.9%)	6,169.5	6,720.3
	rural	34.7	2,129.7 (4.6%)	2,164.4 - (11.8%)
	resorts	-	1,089.4	1,089.4
	Total area	64,179.3 (100%)	205,361.2 (100%)	269,540.5 (100%)

Source: Rotnicki and Borowka, 1992.

Intensive urbanization and economic investment in Poland's low-lying coastal areas is reflected in Table 9. The values of selected variables in the "Linear" and the "Quantity" categories represent some of the potential resources at risk in the low-lying regions of Poland. In addition to the national totals for Poland, resources at risk in the central urban areas of the ports of Gdansk, Szczecin, and Swinoujscie are illustrated using the relevant 1:25,000 topographic sheet for each. Even with exclusion of their wider urban areas, these cities account for 60 percent of the total Polish population below 2.5 meters.

TABLE 9. CULTURAL/ECONOMIC FEATURES BELOW 2.5 METERS

Measurement	At Risk	Poland Total	Gdansk	Szczecin	Swinoujscie
Linear (km)	dikes	1,837.72	21.9	19.8	29.4
	regional roads	905.62	30.5	12.5	17.3
	rail lines	374.14	62.0	12.9	6.5
	port facilities	12.11	----	----	----
Quantity	population	296,510	92,500	50,000	32,620
	road bridges	217	9	6	1
	rail bridges	58	16	3	0

Source: Rotnicki and Borowka, 1992.

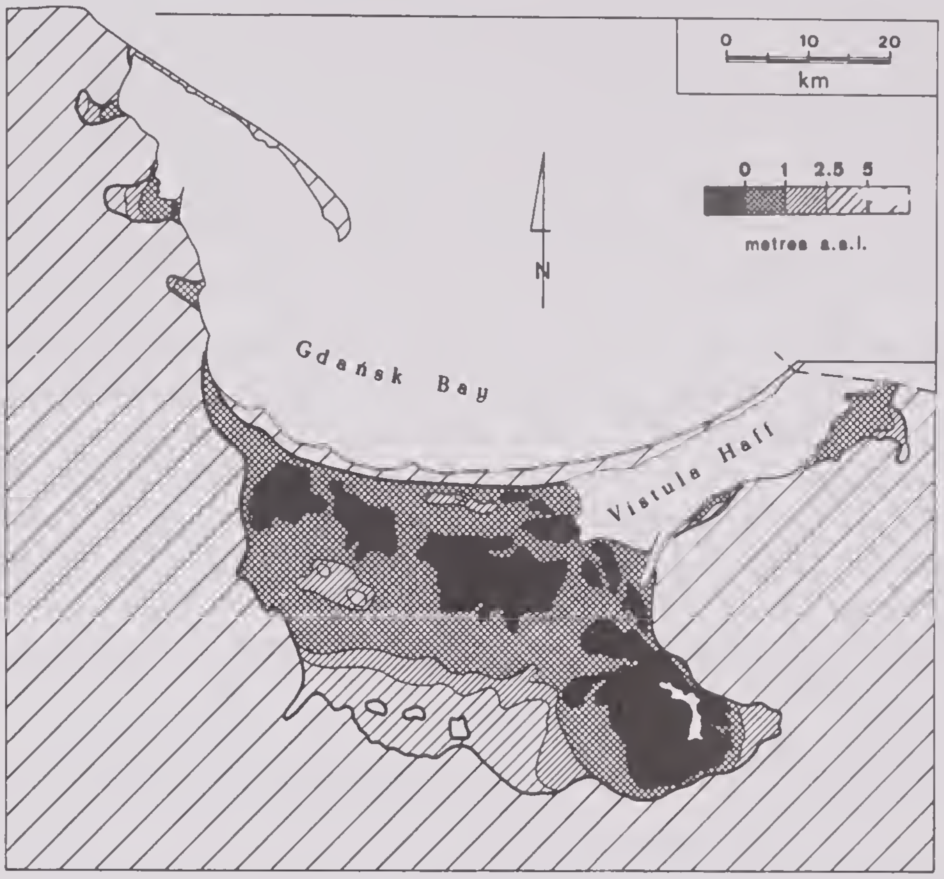
Whereas a large proportion of the settlement and nonagricultural infrastructure in low-lying areas is concentrated in several major urban areas, the development of low-lying agricultural land has resulted in elaborate reclamation and defense of much of the remaining estuarine areas. As shown in Figure 13, a large portion of the land in the Vistula delta is currently below sea level, and most of this area is cultivated or in pasture. Dikes and canals have been successfully employed in the development of intertidal areas. However, a sea level rise of only 0.5 meters would result in the recurrence of the present hundred-year storm-water elevation every 3.5 to 5 years. According to Rotnicki and Borowka (1991), the 0.5-meter rise would most likely necessitate major economic investments, including:

- Upgrading of 120–200 intermediate pumping stations.
- Rebuilding or increasing the height of 1,300 km of dikes.
- Raising the bottoms of 1,500 km^2 of polder.
- New polder construction.

The Risk Quantification research in Poland is revealing very significant future impacts for the national economy. Immediately striking is the finding that Poland has over 183,000 hectares of polders and over 1,800 km of dikes. This latter number is much larger than IPCC estimates (IPCC, CZMS, 1990). Using the calculation of the cost of raising dikes 1 meter, the monetary expense of this option is more than six times the value of the total Poland scenario shown in the IPCC rule-of-thumb calculation (IPCC, CZMS, 1990).

Despite the potential dangers, public and government awareness of the impacts of sea level rise remains low in Poland. Existing levels of development and Poland's continued commitment to port development, shipbuilding, and international trade suggest that a Polish response to accelerated sea level rise will consist primarily of protection in place, new technologies for protection, and rapidly increasing costs for such protection.

FIGURE 13. DISTRIBUTION OF LOW-LYING AREAS WITHIN THE VISTULA DELTA AND ESTUARY



Note that the black areas are currently below sea level (Rotnicki and Borowka, 1991).

SUMMARY OF THE PRESENTED CASE STUDIES

The use of local experts, topographic maps, and ancillary sources and methods has produced a wealth of data at a very low cost. Systematic collection of data based on topographic sheets presents a structured approach that allows for easy updating as new sources are encountered or compiled. As is true with any map data, these tabulations represent a moment in time and will change with alternative economic and political strategies. Yet they form a quantitative basis for assessing cultural and natural landscapes at risk in 11 countries and regions that can be further refined. These data suggest much larger dimensions to the sea level rise problem than hitherto considered, especially in the intertidal region of the world, both in an absolute quantitative sense, as well as from a management perspective.

Each country's data set has the following applications:

- It identifies critical natural environments at risk and provides the quantitative basis for establishing priorities.
- It allows cultural and economic features to be grouped to assess critical issues.

- It provides input to land-use decision making (e.g., agricultural, industrial, urban, and tourism planning).

- It provides a basis for assessing the impacts of sea level rise in local, regional, and national terms.

SCIENCE, MANAGEMENT, AND POLICY IMPLICATIONS

The results of the National Assessments of Risk will help inform future risk assessments, responses, institution building, and legislation with respect to sea level rise. Yet data results and analyses also lead to some fundamental and difficult questions concerning current international efforts that are creating the agendas for science, technology, adaptive strategies, and institutional mechanisms related to sea level rise. The IPCC's Coastal Zone Management Subgroup (1990) has stated that the scientific community is "unanimous in its conviction that the world urgently needs to begin the process of identifying, analyzing, evaluating, and planning adaptive responses and their timely implementation." It has called for the application of comprehensive coastal zone management in all coastal nations by the year 2001 and has deemed necessary a "common methodology" to assess vulnerability to sea level rise. The realization of these efforts will necessitate the concentration of the bulk of international resources that will become available for addressing the sea level rise issue. Apparently the aim is to push ahead using current scientific knowledge, response strategies, and institutional approaches—an objective that may not be wise if important parameters of the sea level rise problem have not been addressed. This could result in wasted effort and misguided priorities as well as increases in economic costs and human vulnerability related to sea level rise.

Specifically, the National Assessments of Risk have raised questions concerning:

- The dominant view in sea level rise studies which considers sea level rise to be a static concept operating in an unchanging environmental setting.

- Methodologies that forecast sea level rise impact scenarios without properly emphasizing the role of human culture in developing and changing the coastal zone.

- The relevance of coastal zone management, as currently conceived, for addressing ongoing developmental processes.

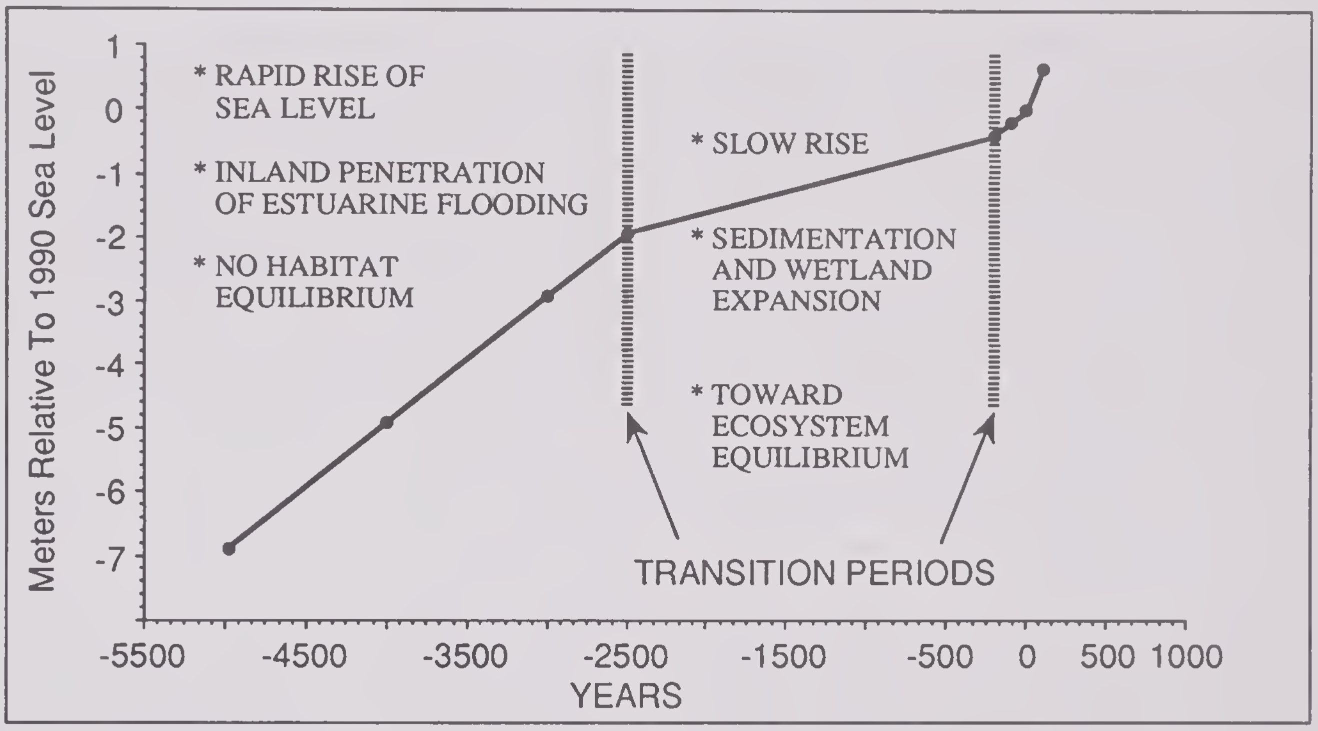
- The current emphasis on transferral of soft and hard technological adaptive strategies, rather than on improving of indigenous approaches to coastal management and on innovative socioeconomic and political strategies to discourage coastal pressures.

ACCELERATED SEA LEVEL RISE AS A STATIC CONCEPT

The efforts of the past several years are early approaches to an understanding of the effects of sea level rise on national institutions, on regional and local economies, and even on the natural systems. However, it is evident that we must soon pass from the consideration of sea level rise as a one-dimensional element that is to be barred from the coast solely by some sort of technological response. Eventually, we must begin to use biosphere-geosphere concepts of equilibrium/disequilibrium that integrate a variety of organic and inorganic inputs into the coastal zone to create functional systems. Sea level rise is one of the driving forces in the equilibrium/disequilibrium mode. Mobility and stability are aspects of a complicated equation.

Figure 14 summarizes a considerable field of knowledge regarding development of the coastal system in a barrier island environment on the East and Gulf Coasts of the United States, and its equilibrium mode relative to rates of sea level rise. It portrays the reaction of the natural system to rates of sea level rise measured in the recent past history of the system. From the middle portion of the figure, we see that most of the modern coastal system is very young—on the order of 2,000–3,000 years. Before that time, as a result of a relatively rapid sea level rise, there were no great expanses of marsh, and the barrier islands were in constant spatial flux. With relative sea level stability, rising about 0.75 mm per year, the present system developed. But instability has now returned. Sea level has risen 2 mm/year for the last several centuries, and the forecast is for much higher rates and increased disequilibrium. Accelerated sea level rise means that the estuarine environmental systems are and will be changing to conditions represented by the steep portion of the curve.

FIGURE 14. ESTUARY EQUILIBRIUM MODEL



Portrayal of the rate of sea level rise and the expansion or attenuation of the natural estuarine habitats in a temporal context. Changing areal dimensions and spatial associations are related to the balance between the volumetric rates of inorganic and organic accumulation in the estuaries and the vertical rate of sea level rise. Estuarine system equilibrium was fostered during the slow rates of rise of the past 2500 years. The rates of rise in the past century, and probably the preceding one as well, exceed the rates of the earlier period (pre-2500 years B.P.) when the estuaries were largely aquatic environments (Psuty, 1992).

This research has very important implications for future attempts at management toward specific environmental goals. Because barriers, estuaries, and numerous other coastal features and environments worldwide have evolved under much slower rates of sea level rise, it is very likely that they will not be able to continue to adapt, adjust, retreat, etc., to more rapid rates of erosion and inundation related to sea level rise. Current science, management, and planning are based on the concept of a simple arithmetic rise of the sea and an accompanying spatial displacement of the natural system (assuming that adequate space is available). However, the creation of disequilibrium initiated by any level of rise may result in much greater relative deterioration, loss, and inundation of the coastal systems. Strategies toward mitigation of the impacts related to sea level rise on many coastlines may need to include provisions for accepting a reduced areal extent of wetlands, increased rates of sediment loss from dynamic shoreline environments, and increased mobility of shorelines.

The misuse of sea level rise as a static concept in an undynamic environment also has important implications for the choice of protection strategies. As has been addressed in the work of Moreira (1991) in Portugal, erecting or raising the height of dikes or walls as a response to sea level rise will not prevent: salinity levels from changing in estuarine environments, displacement of organisms, or deterioration of the estuaries. Nor will it deter development pressures. Holding the shoreline position constant is but one element in the complexity of the coastal zone. The modern-day focus has been on adaptation and structural modification. The case studies give us cause to reconsider such priorities. Much more emphasis should be directed to curbing development, preventing occupation of hazardous areas, and slowing the degradation of natural systems.

HUMAN DEVELOPMENT AS A STATIC VARIABLE IN THE SEA LEVEL RISE EQUATION

National risk assessments are now providing data sets that identify coastal areas at risk under alternative sea level rise scenarios. Whereas the rate of sea level rise is extrapolated into the future, all too often the cultural, ecological, and economic settings onto which inundation is superimposed are considered static variables. Research from a number of critical areas at risk in the developing world suggests that the absolute rise of seas will not be the most important factor in respect to impacts related to sea level rise. In numerous locations, human activity (including the removal of ground water, oil, and sand; vegetative destruction; and shoreline retreat associated with disequilibrium caused by encroaching infrastructure and structural protection) will be more important in accelerating shoreline inundation than sea level rise itself (Ibe et al., 1989; Cambers, 1991; Chen and Chen, 1991; Teh, 1991). Although many developing nations are vigorously pursuing development of low-lying coastal and riverine areas in an attempt to improve social and economic conditions (Sorensen, 1987; Boxer, 1987; Loveson and Rajamanickman, 1989; El-Raey, 1989), very few assessments of the impacts of sea level rise undertaken to date adequately consider the dynamics of cultural and economic systems. For example, a large proportion of future direct and indirect cultural and economic dislocations related to sea level rise will be related to the rate of expansion of urban sites as nodes of industry, tourism, port development, and formal and informal residential and commercial development (Devine, 1992). Current methodology for assessing the risks stemming from sea level rise gives far too little emphasis to incorporating such essential parameters of the sea level rise equation.

The issue of changing human use and occupation of the coastal zone through the temporal dimension is demonstrated in the National Assessment of Risk for Tunisia (Oueslati, 1992). These data (Table 10, column 3) enumerate all the current natural and cultural features of the Tunisian coast, as well as those at risk when sea level rise inundates the coastal zone up to the present 2.0-meter contour. The data reveal significant risk to agricultural lands, but the vast majority of human and economic dislocation will be associated with nodes of urban and tourism development. The nation's largest cities and ports and most industrial and tourist facilities (and all salt production facilities) are very close to the shoreline. The data can be broken down by topographic sheet to reveal the potential risk in the Bizerte, Goulette/Tunis, Sousse, Sfax/Agareb, and Gabes urban areas (Table 10, columns 4–8). Both in absolute terms (column 9) and as a percentage of the national total (column 10), these data reveal a dramatic concentration of risk associated with urban development.

Although these data, as well as the Table 9 data from Poland, allow for the identification of urban sites as the most critical areas, they do not reflect the ongoing cultural, economic, and ecological changes in these rapidly urbanizing areas that will determine future impacts of sea level rise. In his analysis, Oueslati (1992) emphasizes the need to understand the cultural and

TABLE 10. COASTAL LAND USE/LAND COVER IN TUNISIA AND SELECTED TUNISIAN CITIES

Measure-ment		At Risk	Tunisia	Bizerte 1:50,000	Goulette 1:25 Tunis 1: 50	Sousse 1:50,000	Sfax/Agareb 1:50,000	Gabes 1:50,000	5 city total	% of national total
Linear	intertidal	artificial coast	20.0	10.5	7.0				17.5	87%
		beach (w/dune)	193.1	2.5	7.0	23.5		11.0	44.0	23%
		beach	262.8	4.0	1.8				5.8	2%
		cliffs (small)	152.5	13.0	11.7	1.7			26.4	17%
		cliffs	280.8			3.5			3.5	1%
		low loose coast	491.0	16.0	4.0		30.0	12.0	62.0	13%
		low rocky coast	241.2		13.3	4.7			18.0	7%
	0-2 m	bridges	.3						0	0%
		rail lines	34.2	6.0	15.0	8.0	1.2	4.0	34.2	100%
		roads	108.2	2.0	7.0	15.0			24.0	22%
		roads w/bridge	6.2						0	0%
		dikes	8.5						0	0%
Areal	0-2 m	agriculture	12,289.3	256.2	275.0		1,760.0	75.0	2366.2	19%
		residential	575.9			37.5	83.0		120.5	21%
		tourism	1,186.1	137.5		215.0		18.7	371.2	31%
		urban	851.7	130.0	389.0	25.0	90.0	37.5	671.5	79%
		industrial/military	1,677.3	868.3	361.3	50.0	184.3	100.0	1563.9	93%
		salt pans	1,400.0		303.0	212.0	670.0		1185	85%
Quantity		fishing ports	25	2		1	2	1	6	24%
		commercial ports	8	1	2	1	1	1	6	75%
		marinas	2			1			1	50%

(Source: Oueslati, 1992)

ecological contexts in which the data exist. The following excerpts from the Tunisia National Assessment of Risk provide evidence that the evaluation of future sea level rise-related impacts and implementation of response strategies simply on the basis of current levels of development and past experiences would be grossly inadequate:

- In the Gulf of Tunis area, human development has historically been confined to the low deltaic margins, active cliffs, and dune fields. However, recent acceleration of population growth, urban expansion, and tourist development (e.g, suburban Tunis, Sidi Daoud, and Haouaria) has beaches and salinized lowlands.

- On the eastern shore of the Cape Bon Peninsula the coast is densely occupied. But human activities and structures, until recently, have avoided the *sebkhas* and sandy bars isolating them from the sea. Present growth of this region, however, is increasingly in hazardous low-lying areas (e.g., extension of urbanization of the regional capital of Nabeul over a very low alluvial plain).

- In the Sahel of Mahdia region, settlement had historically avoided the immediate shore. Recent development (industries, hotels, residences), however, has taken place in the lowest areas, and beaches are increasingly being developed intensively, especially between Mahdia and Sallakta.

- In the Gulf of Gabes area, development is extending over salt marshes and will experience serious winter flooding as sea level rise combines with heavy rains and spring tides. In Sfax, the second largest city in Tunisia (where sea level rise is four times the world average), most residential growth to the north is extending over salinized areas that are less than 2 meters above sea level. The Chaffar's coast is experiencing residential and tourist pressures in areas less than 2 meters.

As is the case in numerous developing countries, "development" in Tunisia is increasingly concentrated in a few urban coastal centers and encroaches on ever more hazardous environs. Particularly in areas experiencing rapid growth, it will be difficult to obtain accurate risk assessments if only current data are considered.

The research and data from the Gulf of Mexico region (Ortiz et al., 1991; Ortiz and Valverde, 1992) provide another example of the necessity for assessment and management related to sea level rise to be sensitized to trends in human development and alteration of the coastal zone.

The 2,500-km coast of the Gulf of Mexico is, at present, not densely settled or widely developed. However, recently the coastal zone has been undergoing considerable change as a result of port development, petroleum exploitation, industrial siting, agriculture, and tourism. The major risks from sea level rise will be threats to the ecology, infrastructure, and settlement that support the economic development. The data in Table 11 (from 50 topographic maps, 1:50,000-scale, digitized and supplemented with aerial photographs and other maps) reflect current estimates of the natural and cultural features at potential risk to future rise in sea level. Data also are assembled for five important economic centers to illustrate the urban concentration of risk related to sea level rise (Table 12). The last column in Table 12 shows, as a percentage, the total of regional impacts concentrated in these five urban areas. Among the significant statistics, 82 percent of the commercial/industrial frontage and 80 percent of the settlement below 2 meters are associated with these major port areas. These data suggest that development associated with regional ports will most likely account for a large proportion of the cultural and economic dislocation associated with rising seas.

TABLE 11. RESOURCES AT RISK IN GULF OF MEXICO REGION

Measurement	Intertidal Zone		0-2 m above high tide	
Linear km.	natural features			
	mangroves/marsh	540.4	cultural/economic features	
	salt marsh	407.4	roads	291.9
	beaches w/dune	572.6	bridges	14.0
	beaches w/o dune	646.8	canals	178.0
	cliff	44.3	shoreline frontage	
	coral	78.6	harbor	57.6
	cultural/economic features		commercial/industrial	30.2
	dikes	24.7	residential/tourist	15.8
	canals	84.3		
	seawall/jetties	8.5		
Areal hectares	natural features		natural features	
	mangrove	230,797.6	dune fields	31,086.5
	marsh/swamp	234,169.1	cultural/economic features	
	salt marsh	159,709.6	grassland/pasture	501,706.4
	coral reef	1,863.2	agriculture	214,232.5
			settlement	7,951.0

Source: Ortiz and Valverde, 1992.

As in the Tunisian case, the data portray the spatial concentration of risk. However, these data could be misleading from a planning and management standpoint if urban/economic/demographic trends are not thoroughly considered. Specifically, risk assessment in the Gulf of Mexico region must recognize the ongoing, highly-uneven development and the emerging domination of economic centers (largely associated with the tourist and petroleum industries), which are increasingly the sites of the vast majority of port facilities, protective infrastructure, industry, and settlement. The spectacular growth of several Mexican coastal cities over the past decades, including the emergence of several new economic centers, is shown in Table 13. These figures suggest serious danger if future impacts of sea level rise are not determined by extrapolation of the present growth trends in urban/industrial centers.

TABLE 12. RESOURCES AT RISK IN SELECTED URBAN AREAS OF THE GULF OF MEXICO

Measurement	Cultural Features At Risk	Tampico	Gt. Zamora	Veracruz	Coatzacoalcos	Ciudad del Carmen	5 city % of region
Linear inter-tidal	dikes	4.6	0.0	2.0	1.7	0.0	31%
	canals	22.5	0.0	0.0	1.0	0.0	8%
	seawall/jetties	5.8	0.1	0.0	1.7	0.0	90%
Linear 0-2 m	road	20.0	54.0	4.0	28.7	4.4	35%
	bridges	1.2	0.6	0.5	1.3	0.0	9%
	canals	0.0	0.0	0.0	13.7	0.0	3%
	harbor	16.3	1.4	12.0	9.0	3.0	80%
	comm/industry	8.4	0.0	8.0	4.9	1.8	82%
	resid/tourism	0.0	0.9	4.0	4.1	1.2	67%
	polyducts	15.0	34.0	0.0	28.0	0.0	31%
	rail lines	26.0	26.0	1.2	43.8	0.0	40%
Areal 0-2 m	grass/pasture	3,630.6	66,610.0	742.0	0.0	1,630.7	13%
	agriculture	18,992.9	2,254.9	533.5	24,004.6	5,040.7	25%
	settlement	2,387.8	65.9	2,269.1	0.0	441.5	80%

Source: Ortiz and Valverde, 1992.

TABLE 13. GROWTH OF MEXICO'S COASTAL CITIES, 1960-2000

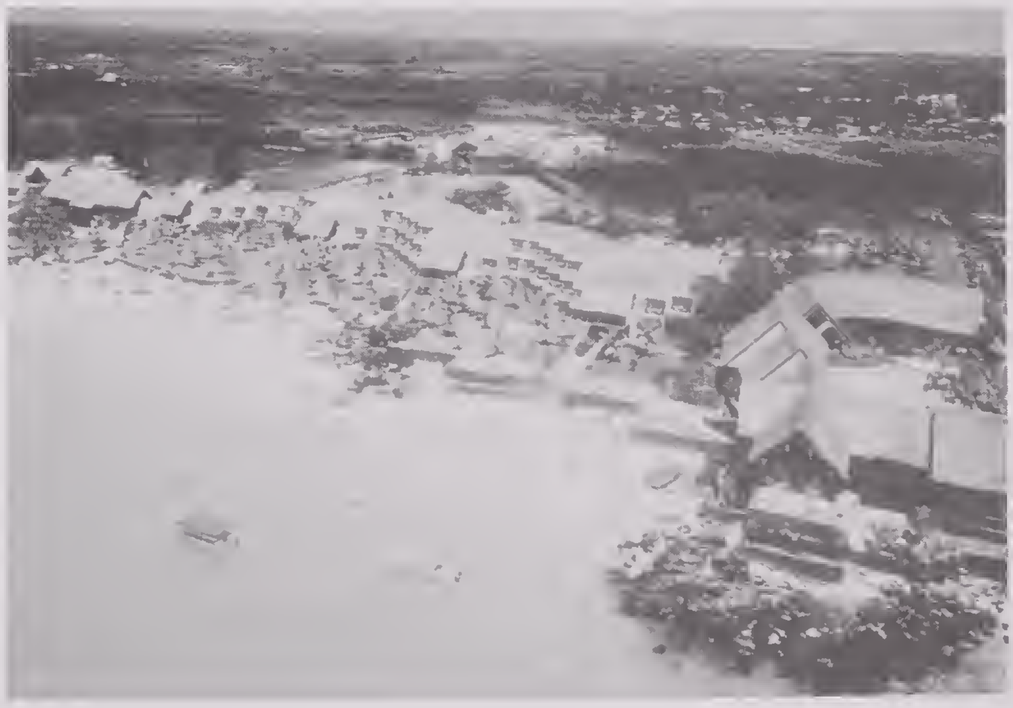
CITIES	1950	1960	1970	1980	1990	2000
Campeche	31,272	43,874	69,506	128,434	147,551	179,263
Carmen	11,603	21,164	34,656	72,489	84,016	103,631
Cancun	--	--	--	--	33,273	--
Chetumal	7,247	12,855	23,685	56,709	64,928	80,850
Cozumel	2,332	2,915	5,858	19,044	20,807	26,115
Tampico	94,345	124,894	18,059	267,957	313,314	371,414
Matamoros	45,846	92,327	137,749	188,745	234,697	282,108
Veracruz	101,221	153,705	230,220	305,456	415,456	511,678
Coatzacoalcos	19,501	37,300	69,753	186,129	211,255	264,489
Minatitlan	22,455	34,350	68,397	145,268	168,239	208,388
Tuxpan	16,096	23,262	33,901	56,037	64,940	77,986
Alvarado	8,840	12,548	15,792	22,633	26,109	30,571
Panuco	6,615	8,818	14,277	26,652	30,483	37,040
Gtz. Zamora	4,480	6,518	9,099	15,037	17,347	20,772
Progreso	13,339	17,060	21,352	30,183	34,190	39,672

Source: Ortiz et al., 1991.

COASTAL ZONE MANAGEMENT PLANNING

Many developing countries are experiencing an ongoing and accelerating trend toward increased coastal orientation of settlement and economic investment (Devine, 1992). As a result, the economic growth of many countries is increasingly dependent on development of precisely those nearshore areas that will be most threatened by sea level rise. For example, many countries with high proportions of investment in coastal tourism are continuing to direct national resources into tourism development and/or defense of the industry (Figures 15 and 16). In Mauritius, where 98 percent of tourism depends on sandy beach resorts, during the past 15 years tourism's contribution to foreign export exchange has increased from 6 to 17 percent (Jogoo, 1992). Today, 21 hotel projects are proposed that would increase room capacity by 50 percent, all at the shoreline. Development pressure is not abating despite increased awareness of sea level rise. It is likely that even with comprehensive coastal zone mangement planning, problems afflicting the coast will remain outside the realm of authority of the institutions responsible for implementing such a conceptual framework, and/or more pressing problems will prevent the realization of coastal zone management planning.

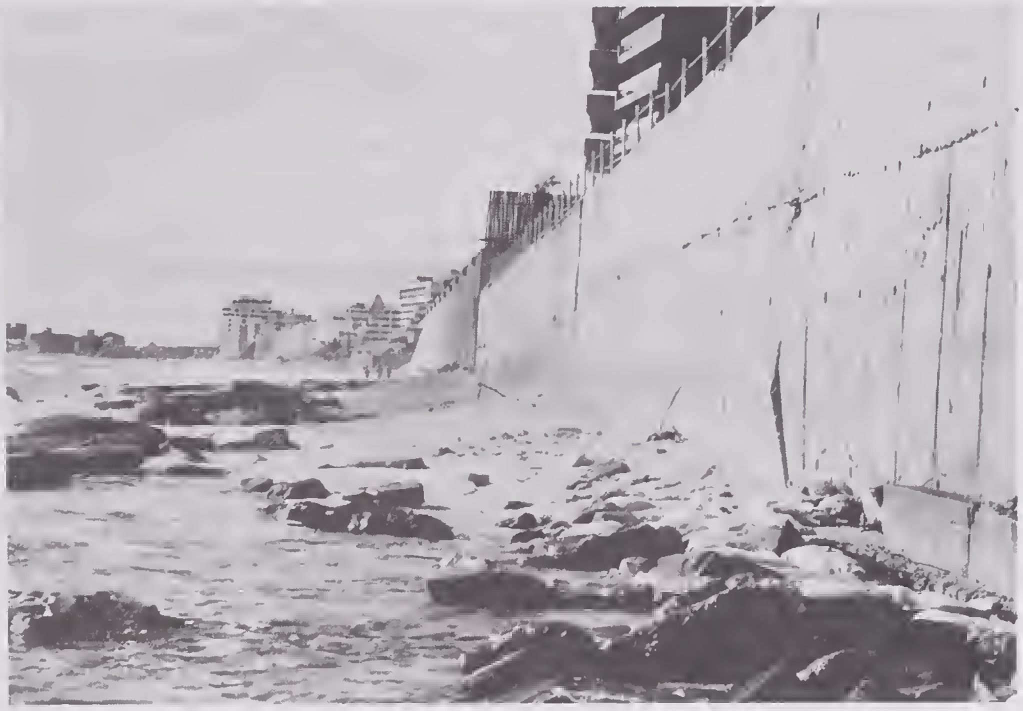
FIGURE 15. COASTAL TOURISM DEVELOPMENT OVER LOW ELEVATIONS IN MAURITIUS



Source: Fagoonee, (1991).

· Economic and demographic trends, combined with cultural, economic, and political constraints to the adoption of structural and institutional responses, suggest that the emphasis on these options may be misplaced. Even if significant progress is made toward alleviating institutional and managerial barriers to coastal management, and even if response strategies are developed, coastal areas in developing countries are committed to large increases in development and degradation, just as they are locked into higher sea levels. Thus, for most developing countries, it will be essential to incorporate such development trends into current assessment methodologies to accurately portray national vulnerability to the impacts of sea level rise and to conceptualize effective management and response strategies.

FIGURE 16. PROTECTIVE STRUCTURES AT CANCUN, QUINTANA ROO, MEXICO (JANUARY 1990)



Older tourist development requires large and ongoing investments in structural protection to stabilize the shoreline and defend buildings.

Some of the difficulties inherent in implementing coastal zone management have been identified in the earlier case studies (and, more generally, in the work of Sorensen (1987)). The National Assessment of Risk for Sri Lanka (Wije and Adikaramge, 1992) provides more detailed commentary on the limitations inherent in coastal zone management planning as currently conceived.

In Sri Lanka, coastal zone management plans have recently been completed and revised without input from the 530 fishing villages and associated cooperative fishing societies that have, historically, been the managers of much of the Sri Lankan coastline. Coastal zone management planning also does not consider the existing and potential risks for the large percentage of Colombo residents occupying slums or shanties in lowland, flood-prone areas. Even present methodologies for assessing the risks of sea level rise will not capture the risk to those settlements of Colombo that are above the 2-meter contour but that will be affected by the backup and flooding of the numerous canals and channels that intertwine throughout the metropolitan region (Wije and Adikaramge, 1991).

Despite the many needs for improving international sea level rise efforts, the largest problem of the sea level rise endeavor may be the lack of coordination and application of existing knowledge. For example, the U.S. Agency for International Development has been instrumental in developing coastal zone management planning in Sri Lanka, yet only very recently was the coordinator of the project made aware of the implications of sea level rise when presented with findings from research sponsored by the U.S. Environmental Protection Agency (Wije and Adikaramge, 1992).

If problems are inadequately conceived, it is likely that the limited resources for scientific, institutional, and response strategies will be misallocated and could result in increasing risk and vulnerability.

STRUCTURAL RESPONSE STRATEGIES

The past response to coastal problems (in developed and developing countries) has been largely one of preservation of land uses and protection of economic infrastructure. This not only has resulted in the maintenance of settlement patterns and economic ventures but also has encouraged expansion of human activities in these same areas, despite the certain knowledge of these locations as increasingly hazardous environments. As can be appreciated from the case studies of Guyana and Portugal, as well as numerous earlier studies of sea level rise (e.g., Asthana, 1989; Ibe et al., 1989; Roy and Connell, 1989; Shannon, 1990; Oueslati, 1991; Teh, 1991), attempts at structural protection in developing countries have had a very mixed record of success, with an increasingly poor likelihood of applicability as sea level rises. It is true that the failure of structural response can be linked to economic constraints, but, as discussed in the Guyana case, a number of other issues need to be addressed. Moreover, in the vast majority of developing countries, socioeconomic conditions are deteriorating, which will most likely increase the obstacles to effective implementation of structural responses (with the exception of protection of the most strategic economic areas).

There are difficulties inherent in adapting universal response strategies to vastly different physical, cultural, and economic settings, and there are questions concerning appropriate decision making in the implementation of particular response strategies. For example, investment in response strategies focuses primarily on capital-intensive sites, which are often poorly conceived investments in the first place. Moreover, maintenance of these areas will be at the direct expense of adjacent areas (environments, settlements, occupations) and at the indirect expense (because of lack of remaining funds) of less capital-intensive coastal developments, which are, most often, more ecologically, culturally, and economically sound. Studies suggest that national and international investment in structural protection often ignores the needs, experiences, capabilities, and interests of the indigenous populations (Roy and Connell, 1989; Adam, 1991; Wije and Adikaramge, 1991; Sullivan and Hughes, 1991; Daniel, 1992). Faced with these dilemmas and a scientific and policymaking community poised to push ahead without confronting these difficult issues, developing nations may be tempted to ignore sea level rise considerations.

The significant differentiation at the regional, national, and local scales with respect to societal vulnerability to accelerated sea level rise has received extensive commentary. The differential capabilities between and among communities to mitigate sea level rise impacts have received much less attention, though this are central to understanding the global dimensions of human vulnerability (Massei, 1990). In the case of the large and increasing poor segments of society in developing countries, very little attention has been given to the potential dislocations and alternate response options (Devine, 1992). The initial stages of sea level rise will directly affect millions of coastal inhabitants whose way of life—as well as housing, food, fuel, etc.—is dependent on the delicate balance struck within the existing natural systems. Current response strategies do not adequately consider such dislocations.

Research assessing the potential impacts on informal settlements in the developing world has only recently been initiated (Devine, 1992), although researchers in Sri Lanka and Papua New Guinea have brought attention to the problem (Sullivan and Hughes, 1991; Wije and Adikaramge, 1991). Data from Papua New Guinea again demonstrate how the very early stages of sea level rise will impose extensive societal dislocation. A 0.5-meter rise will be particularly disruptive to structures associated with the informal settlements of the towns of Port Moresby and Lae (Table 14). As is the case in many parts of the world, Papua New Guineans increasingly inhabit low-lying and intertidal regions, and their houses, occupations, and supporting ecosystems depend on a delicate balance struck with current sea levels (Figure 17).

TABLE 14. INUNDATION OF LAND, BUILDINGS, POPULATIONS, AND ROADS IN PORT MORESBY, AND LAE, PAPUA NEW GUINEA

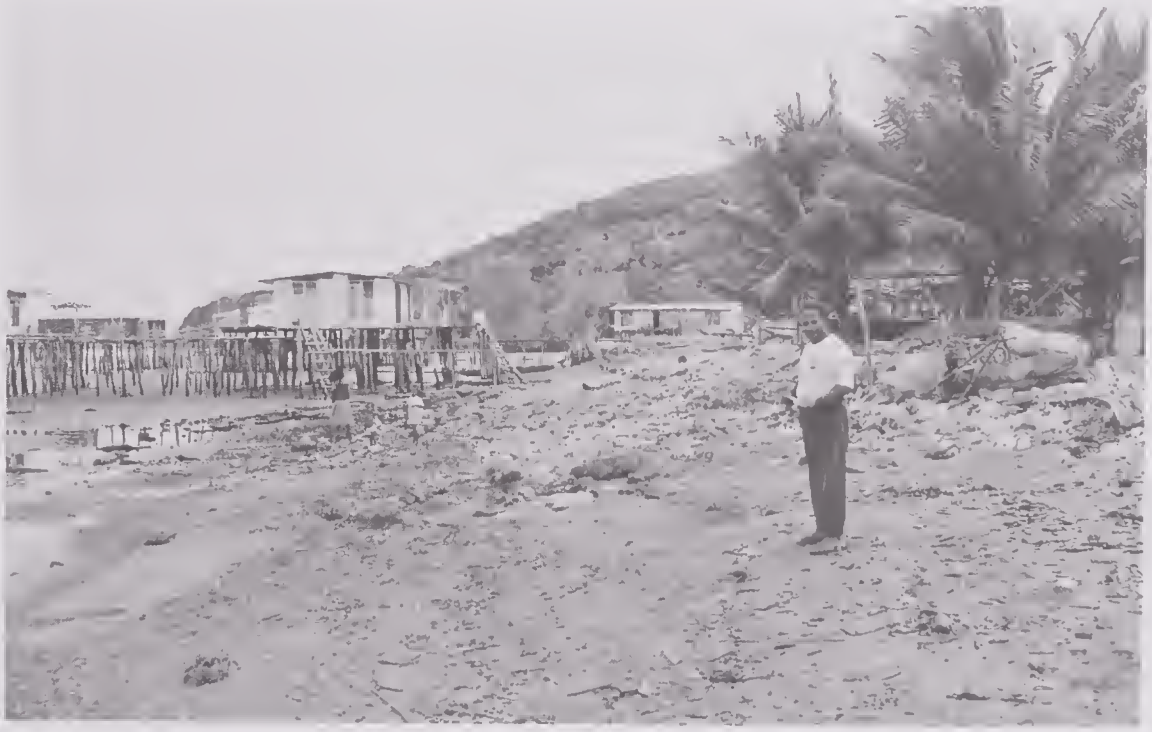
	Projected rise (meters)	Area inundated (hectares)	Total area inundated	Buildings lost (cumulative total)		Population affected (cum. total)	Km. of road lost (cum. total)
				formal[1]	informal		
Port Moresby	0.5	36	36	50	960	9,500	5
	1.0	30	36	100	1,030	10,100	10
	1.5	10	76	110	1,065	10,800	15
	2.0	11	87	165	1,105	12,000	20
Lae	0.5	10	10	0	16	160	0.5
	1.0	25	35	*10	86	860	1
	1.5	250	285	*28	158	1,580	3
	2.0	15	300	72	270	3,200	5

Source: Sullivan and Hughes, 1991.

[1] Formal structures are those built of higher-cost commercial materials, and which have services connected (i.e., electricity, water, and sewerage). Informal structures are built of a wide variety of generally lower-cost materials, and most do not have electricity, water, or sewerage connections.

* Mainly commercial buildings, no resident population.

FIGURE 17. TYPICAL DWELLINGS ON THE SOUTHERN PAPUA NEW GUINEA COAST



oastal villages built over the tidal zone are at high risk to rising seas (Sullivan and Hughes, 1991).

CONCLUSION

The numerous case studies completed, under way, and proposed in several countries provide some hope that awareness and research of accelerated sea level rise are increasing, and that there will be careful consideration of responses and institutional strategies. But for the vast majority of developing nations, even the most basic research is not likely to be initiated in the near future, and knowledge of sea level rise is not changing the factors leading to concentrations of large populations and development at risk in the coastal zone. It is likely that the consideration of the concept of sea level rise as an objective at the national institutional level is close to nonexistent anywhere in the world.

In many parts of the world, forms of settlement, agriculture, fishing, and capital-intensive industry have evolved because of and in spite of the delicately balanced low-lying and intertidal coastal and estuarine areas. Our researchers report that these trends in human occupation are continuing, and that the potential for adopting response strategies and legal and institutional changes is a very complex process involving a host of political, cultural, and economic issues—in which no obvious intervention is occurring. For example, effectively addressing sea level rise will depend, to a great extent, on the economic and political stabilities of developing nations. But the economic growth of many nations is increasingly dependent on development of precisely those nearshore areas that will be most threatened by sea level rise.

Our reports, to date, suggest that the dilemma for developing countries is not one of a "challenge of a rising sea level," but one of a largely unmitigatable hazard. For the majority of coastal countries, there is an incomplete consideration of the magnitude of future impacts and of the complexities for response and management. The point that should be presented to the international community (e.g., through the IPCC Response Strategy Working Group's participation at United Nations Conference on Environment and Development), is not that global vulnerability is largely known. Nor should it be inferred that past and current experience can suggest effective response and institutional management. This is not the case. It should be emphasized how far we have come (with very limited resources) in assessing the dimensions of global vulnerability to sea level rise and the opportunities for response in a few of the most critical areas. Based on these findings, the most critical contributions to be made regarding the potential impacts and responses to a global-warming induced sea level rise include:

- Improved assessment of the range and probable magnitude of global impacts, based on *current* ecological and cultural data from a number of countries.

- The complexity of solutions because of their embedded context in ongoing economic and political problems.

- The far-reaching societal implications that will be directly and indirectly imposed on the world's nations.

ACKNOWLEDGMENTS

The authors of this paper extend their sincere appreciation to their several colleagues who contributed the information contained in the national reports on the impacts of sea level rise. Their patient inquiry into institutional policies and their interpretation of the magnitudes of coastal resources at risk were instrumental in shedding light on the many implications and ramifications associated with sea level rise.

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THE IMPACTS OF SEA LEVEL RISE ON COASTAL AREAS: SOME GLOBAL RESULTS

F.M.J. Hoozemans, M. Marchand,
H. Pennekamp, and M. Stive
Delft Hydraulics
Emmeloord, The Netherlands

R. Misdorp and L. Bijlsma
Ministry of Transport and Public Works
Rijkswaterstaat, Tidal Waters Division
The Hague, The Netherlands

SUMMARY

Assessment of the vulnerability of the various resources of the world's coastal zones to an acceleration of sea level rise and related climate change effects requires detailed global information on the distribution, density, and state of the resources and on the impacting hazardous events. For many resources, such as ecosystems, data on a global scale are not readily available. Another complication is that in order to assess the consequences of hazardous events, the response of coastal systems and their response time scales need to be known at a sufficient level of accuracy, which is not generally the case. Within the limits of these constraints, this study considers the following three resources of the coastal zone and accompanying impacts:

- Population at risk (i.e., the number of people subject to regular flooding) on a global scale.
- Wetlands at loss (i.e., the ecologically valuable coastal wetland area under a serious threat of loss) on a global scale.
- Rice production at change (i.e., the potential changes in coastal rice yields due to less favorable conditions) in South, Southeast, and East Asia.

The present findings on global vulnerability are as follows.

Globally, a sea level rise of 1 meter could double the number of people vulnerable to coastal storm surges.

- At present, 100–200 million people are estimated to live below the annual storm surge level. About 20 percent of this population experiences flooding annually.
- An additional 1-meter rise above the current mean sea level would increase the number of people subject to annual flooding by about 50 percent, when coastal defense systems would be maintained at their present efficiency levels. If a population growth scenario were adopted, the number of people subject to annual flooding would double by the year 2020.
- When coastal defense systems are allowed to respond naturally to the increased stress as a result of the accelerated sea level rise (no maintenance of present efficiency levels), the number of people subject to annual flooding would rise dramatically.

- Because of differences in the regime of storm surge events, the increase of flood risk resulting from accelerated sea level rise is larger than average for small islands, the southern Mediterranean coast, the African Atlantic coast, and the Indian coast.

- Increases in severe storm frequency and intensity would further increase the number of people subject to the annual flooding.

Globally, the projected impact of a 1-meter sea level rise on coastal wetlands is alarming.

- Worldwide over 900,000 km^2 of coastal area can be classified as "areas of international importance," indicating that their character is in accordance with the criteria set by the RAMSAR Wetlands Convention. One-third of this coastal area consists of coastal wetlands (salt marshes, intertidal areas, and mangrove forests), which are of great ecological and economic value.

- Coastal wetlands are disappearing at an increasingly rapid rate worldwide as a result of such human activities as enhanced subsidence and shoreline protection, blocking sediment sources for wetlands, and land development activities.

- An acceleration of sea level rise would increase the rate of net coastal wetland loss. In combination with human activities, a 1-meter sea level rise over the next century would threaten half of the world's coastal wetlands of international importance. In some areas, coastal wetlands could be virtually eliminated, because their ability to migrate inland would be limited over such short time scales.

- Losses of coastal wetlands of international importance are expected to be larger than average for the coasts of the United States, the Mediterranean Sea, the African Atlantic, East Asia, Australia, and Papua New Guinea.

A considerable part of the world's rice production is located in regions vulnerable to accelerated sea level rise.

- Approximately 85 percent of the world's rice production takes place in South, Southeast, and East Asia. About 10 percent of this production is located in areas that are estimated to be vulnerable to accelerated sea level rise, thereby endangering the food source for more than 200 million people.

- Less favorable hydraulic conditions may cause lower rice production yields if no adaptive measures are taken. Especially in the large deltas of Vietnam, Bangladesh, and Myanmar (Burma), serious production reductions may be expected.

INTRODUCTION

Stimulated by the efforts of the Coastal Zone Management Subgroup (CZMS) of Working Group III on Response Strategies of the Intergovernmental Panel on Climatic Change (IPCC), a growing number of countries (currently more than 25 all over the world) are assessing the vulnerability of their coastal zones to accelerated sea level rise (ASLR). As each coastal country undertakes such studies, that information will assist in providing a global picture of the potential problems of ASLR on coastal resources and of the level of effort required in response. One of the aims of the CZMS is to provide a worldwide estimate of socioeconomic and ecological implications of ASLR, based on the information made available through the case studies. Waiting for a sufficient number of country case studies to be completed would take too long in view of the United Nations Conference on Environment and Development. Therefore, the primary objective of the study (Delft Hydraulics and Rijkswaterstaat, 1992) summarized here is to generate preliminary vulnerability results on a global scale. A secondary objective is to provide a reference for country case studies.

The incompleteness of the underlying global data and many of the assumptions about physical processes, physical and socioeconomic boundary conditions limit the accuracy of the country-by-country results presented in the underlying study report (Delft Hydraulics and Rijkswaterstaat, 1992). Therefore, it is necessary to only rely on more aggregated results. When aggregated, the results are expected to be more reliable, since inaccuracies in both input data and impact responses will tend to average out.

This paper only presents a concise description of a more comprehensive study. The interested reader is referred to the underlying study report. The nature of this paper does not allow for systematic referencing, but a selection of references that were used appears at the end of this paper.

METHODOLOGY

In order to define and assess the vulnerability of a coastal zone to ASLR, uniform procedures are needed, so that global, regional, and national studies on the impacts of ASLR can be compared and integrated. The Common Methodology ("The Seven Steps to the Assessment of the Vulnerability of Coastal Areas to Sea Level Rise—A Common Methodology" (CM), 1992), developed by the CZMS in 1991, suggests a number of these procedures. Crucial to these procedures are the concepts of values at risk, values at loss, and values at change, which help to determine impacts in measurable and objective terms. These and other concepts of the CM are used in the present study.

VALUES AT RISK, AT LOSS, AND AT CHANGE

In the present context, the concept of *risk* is defined as the consequence of natural hazardous events times the probability of the occurrence of these events, *without* taking the system response into account. The concepts of loss and of change are defined as the consequences of natural hazardous events times the probability of the occurrence of these events, *with* taking the system response into account. The natural hazardous events vary from global events as eustatic sea level rise, to regional events as subsidence, changing rainfall, or increase of storm surges. The socioeconomic or physical response and the intrinsic time response scale of the relevant "system" (people, agriculture, ecosystems) determine the type of hazardous event that is relevant.

The concept of risk is considered to be appropriate in the context of assessing the consequences of ASLR and related climate changes to the coastal zone population and nearby economic values. The short-term consequences of flooding events to population vary obviously from minor effects, such as flooding of peoples' goods, to the possibility of loss of life. It is considered not realistic to predict any changes these events have on the behavior of the population in the longer term. Although frequent flooding leads to migration, this is not the case for such countries as Bangladesh, where migration is not a realistic alternative, or for some barrier islands in the United States, where a reliable warning system allows for temporary evacuation. Therefore, the concept of risk, rather than the concept of loss or change, is applied to indicate the impacts of sea level rise on the populations of the coastal zone.

The concepts of *change* and of *loss* are considered essential in the respective contexts of agricultural production and ecosystems. In these cases, it is not so much the short-term flooding events that determine the consequences on these resources, but rather the persistence of the average longer-term hydraulic changes, of which the eustatic forcin—and in some cases including the regional forcing—of ASLR are the most important. The probability of the occurrence of ASLR is assumed to be 100 percent; only the rates of change are subject to discussion (see, e.g., Titus and Narayanan, 1992, these proceedings).

As indicated, the determination of values at loss or at change requires taking account of the system response in assessing the consequences of the hazardous event or combination of events. This in turn requires the introduction of the time rates of change of the events. In the current context (focusing on coastal wetlands and rice production), we only have considered the rate of change of eustatic plus local sea level rise to be of importance. Also, we have adopted only one scenario value—1 meter per 100 years. In a more sophisticated approach, one could evaluate results in a probabilistic manner by using scenario values for ASLR and related frequencies of exceedance and could present the outcome in probabilistic terms.

DELINEATION OF THE COASTAL ZONE

To determine the impacts of ASLR on the coastal zone resources that are the topic of the present study (population, ecosystems, and rice production), it is necessary to delineate the coastal zone areas in which the risks, losses, or changes will occur. With respect to ecosystems and rice production, the delineation is based on the information given by the consulted data bases themselves. For the population at risk, the information was generated for this study, which implied special difficulties, since account has been taken of a detailed zonation in terms of areas and accompanying flooding frequencies, including those due to storm surges.

BOUNDARY CONDITIONS AND SCENARIOS

In line with the requirements of the CM, the different impacts are compared for different scenarios of the external boundary conditions. These boundary conditions and their scenarios are:

- The *rate of ASLR*, for which the CM suggests to consider rises of 0.3 and 1.0 meters by the year 2100, versus the present situation. The present study only compares the 1.0-meter scenario to the present situation.
- The *socioeconomic development*, for which the suggestion of the CM is adopted to consider no development versus a predicted development over 30 years.
- The *response strategy*, for which the suggestion of the CM is adopted to consider only the minimum vs. the maximum option—i.e., no measures vs. full measures.

TIME SCALES

The CM purposely chooses a different time scale for the various scenario variables.

- For ASLR, 100 years is assumed, so as to ensure that the gradual, but often irreversible, impacts of this large-scale (in time and in space) phenomenon with a large inertia are clearly indicated.

- For development, 30 years is assumed, since it is virtually impossible to make a reliable prognosis over 100 years.

- For response measures, no time scale is assumed, since a good first-order estimate of the adaptation costs may be obtained by assuming an instantaneous rise of mean sea level for the design of protection measures, thus preventing the complications of specifying measures in time and of economically evaluating these measures using financial depreciation methods.

Only in the assessment of values at change and at loss is the time scale relevant, since it requires the prediction of the response of the system. Lack of data and of knowledge of the system's response limit the accuracy of the estimate of resources at change and at loss.

POPULATION AT RISK

SPECIFICATION OF METHODOLOGY

As mentioned above, the concept of risk is considered to be most appropriate for the assessment of the vulnerability of population in the coastal zone, since it indicates the consequences of the impact *without* taking the response into account. It is considered unrealistic to make a prognosis of population response to increased flooding.

In line with the CM, *population at risk* is defined as the product of the population density in a certain risk zone and the probability of a hazardous flooding event in this risk zone, which products are to be summed over the risk zones. The resulting number is to be interpreted as the expected number of people subject to flooding events per unit of time. This "risk value" is able to reflect both the changes in the population in the risk zone and the changes in flooding frequency due to ASLR.

The study attempted to estimate as precisely as feasible the population at risk, so that effects of changes in the boundary conditions can be made explicit. Therefore, the study took into account a detailed zonation in terms of areas and accompanying flooding frequencies, including those due to storm surges. For instance, first-order storm surge calculations were performed for the world's coastlines, producing flood levels for the 1 in 1, 1 in 10, 1 in 100, and 1 in 1,000 year storms, which were increased with ASLR, subsidence, and pressure effects. Figure 1 presents a global distribution of the thus derived hydraulic regimes per country. The determination of the areas subject to these flooding events requires the availability of detailed area information and information on the physical process of flooding. Obviously, all of these items could only be considered to a limited degree. Some of the consequences this implies are discussed later in this paper.

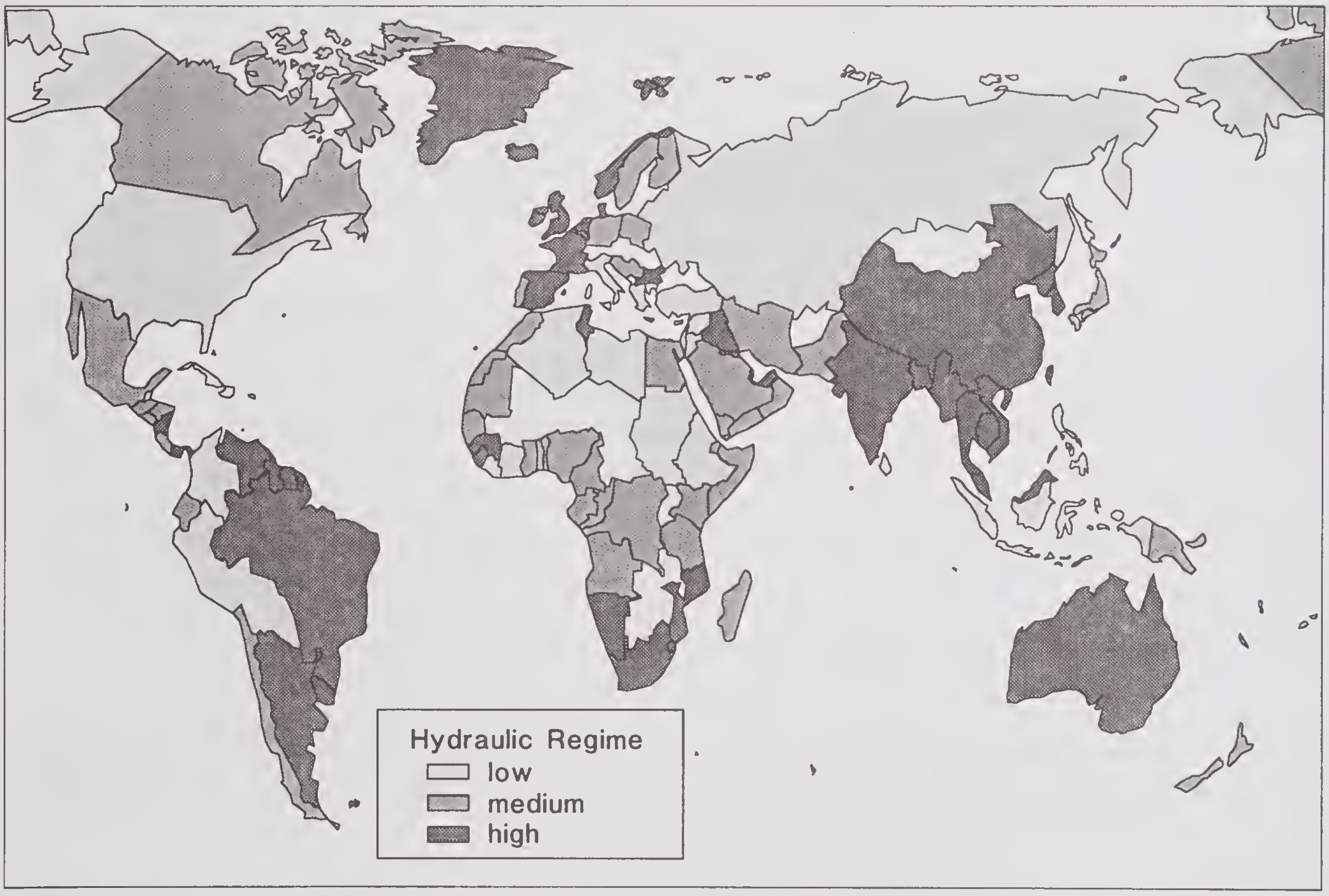
As mentioned earlier, for the population at risk, a systematic variation of the boundary conditions was considered. In effect, this paper compares the vulnerability for the following situations ("future state" refers to a development scenario of 30 years; "ASLR" refers to a 1-meter rise every 100 years; "measures" refers to full protection):

- The present state of the countries without ASLR.
- The present state of the countries with ASLR without measures.
- The future state of the countries with ASLR without measures.
- The present state of the countries with ASLR with measures.
- The future state of the countries with ASLR with measures.

In summary, the following steps were undertaken to determine the population at risk for the various scenarios:

Step 1	Assessment of the maximum height contour of the flood-prone coastal zone, taking into account present and future hydraulic conditions.
Step 2	Calculation of the surface area captured between the coastline and the maximum height contour (maximum potential impact zone).
Step 3	Calculation of the surface area of risk zones, with accompanying flooding frequencies, accounting for the inundation process.
Step 4	Assessment of the present state of protection against flooding in the low-lying countries.
Step 5	Calculation of population densities for the present and the future states.
Step 6	Calculation of population at risk for the different scenarios considered.

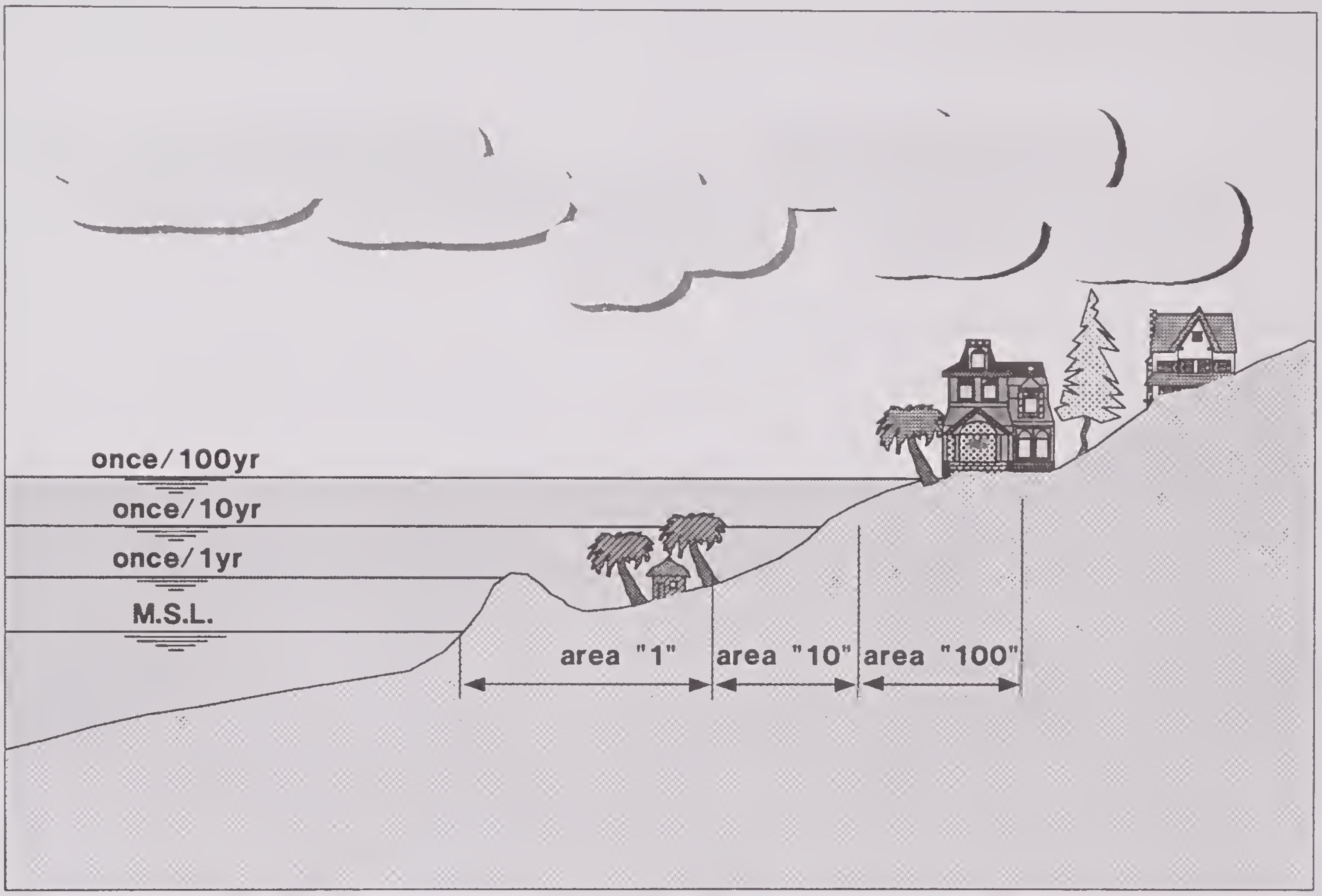
FIGURE 1. GLOBAL DISTRIBUTION OF THE HYDRAULIC IMPACT LEVELS



The data for this figure were derived from present storm surge levels.

Each of these steps is discussed in detail in the underlying study report. A simplified illustration of some aspects related to the above steps is given in Figure 2. As stressed above, the detailed country-by-country results have only limited accuracy and validity. Therefore, aggregated results are presented, but first a discussion of some of the assumptions and associated effects is in order.

FIGURE 2. HYDRAULIC IMPACT AREAS



Simplified illustration of the hydraulic impact areas, as belonging to the different levels of exceedance. Note that area "10," for example, represents the surface area between the once per 1-year and the once per 10-year extreme surge level.

SOME ASSUMPTIONS AND THEIR EFFECTS

LIMITATIONS OF DATA SOURCES

The global data sources that were used allowed only for a limited spatial resolution of a number of variables—e.g., population distribution, height contours, surface areas between height contours. This introduces inaccuracies and requires assumptions, which all lead to inaccurate results on the scale of countries itself. Verification has shown that averaged results on the scales of regions are accurate.

NO PHYSICAL SYSTEM RESPONSE

The assessment of population at risk ignores any physical changes of the coastal environment over the course of time. Although this does seem in many cases to be a realistic assumption because of the human restrictions of sediment availability (river regulation, river damming, coastal protection), it is not generally true (as in Bangladesh's Ganges Delta). However, the effects on the population risk numbers are estimated to be of second order.

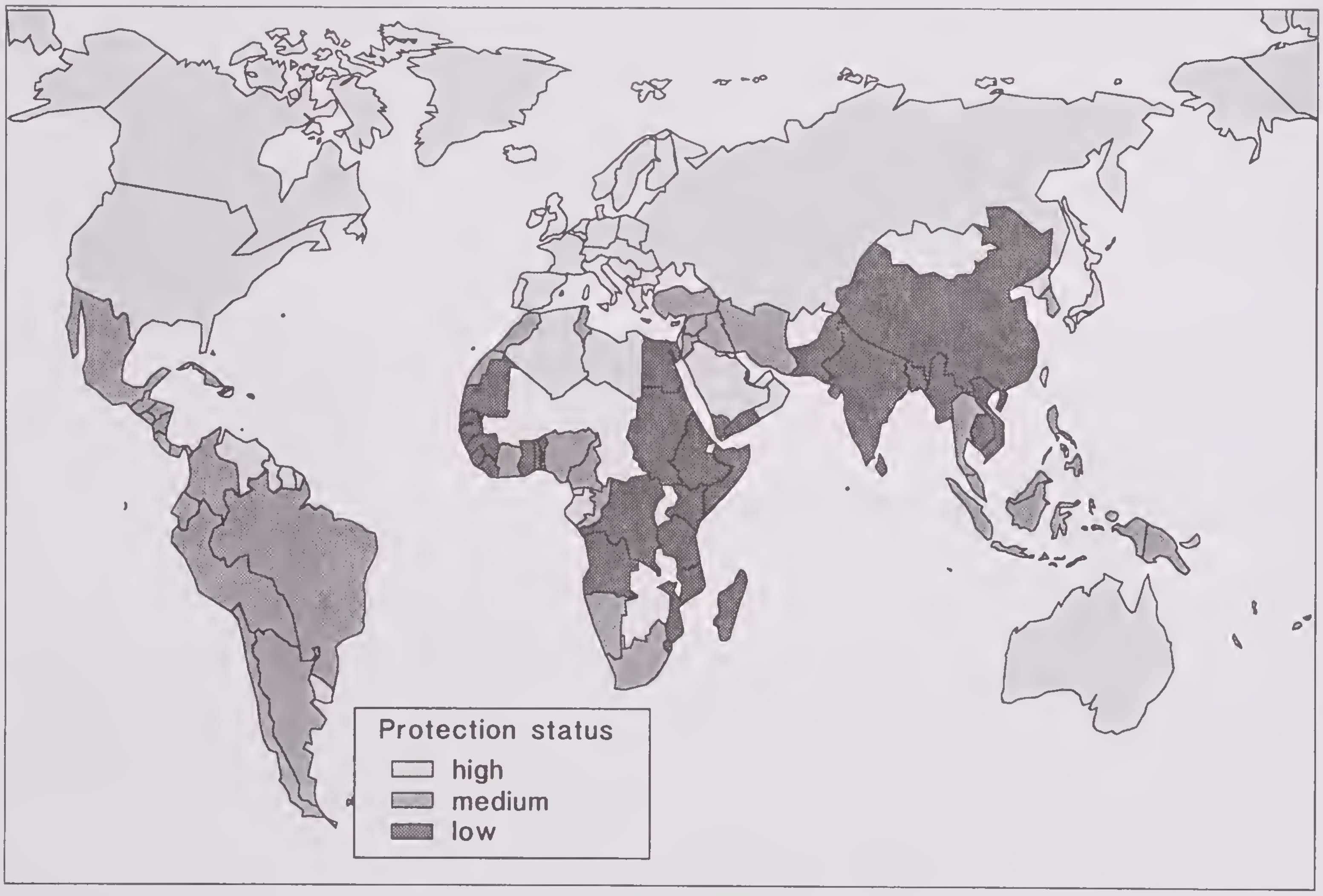
GLOBALIZATION OF HYDRAULIC CONDITIONS AND REGIONAL EFFECTS

Assumptions had to be made about the additional effects of increasing the storm surge levels (e.g., subsidence, tides, barometric pressure). These estimates will again limit the accuracy of the results on the scale of countries, but less so on the scale of regions.

ESTIMATE OF PRESENT PROTECTION STATUS

Since there is no global information on the present protection status of the world's coastlines, it was assumed that the estimate could be based on present GNP per capita. By variation of the estimate, the accuracy bands of the results were derived Figure 3 illustrates the thus derived global protection status.

FIGURE 3. GLOBAL DISTRIBUTION OF PRESENT PROTECTION STATUS



Derived from the gross national product figures for each country.

AGGREGATED RESULTS FOR POPULATION AT RISK

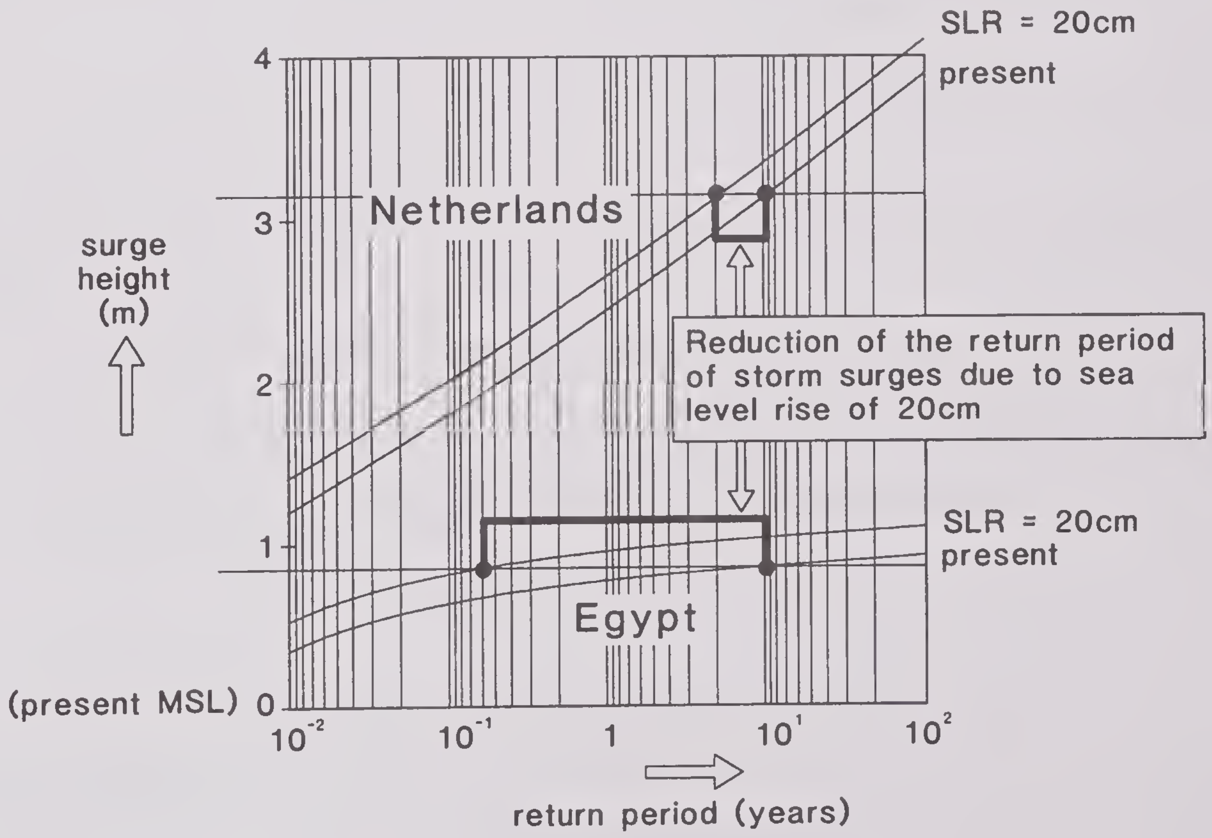
- One hundred to two hundred million people live below the height contour corresponding to the one per year storm surge level. Various estimates of the "coastal population exist," such as "two-thirds of the world population live in the coastal zone," or "by the year 2000 six billion people will live within 60 km from the coast." This study tried to keep to the very strict definition of people below the mentioned height contour.

- In the case of an additional 1-meter rise in sea level, and ignoring any physical or human responses to this effect, the number of people experiencing flooding or inundation will increase by about 50 percent. Under the adoption of a 30-year population growth-rate, this figure will double.

- Because of differences in the regime of extreme water-level events (especially due to differences in decimating height levels (see Figure 4), the increase of flood risk in low-lying coastal regions due to ASLR is larger than average for small islands, the southern Mediterranean coast, the African Atlantic coast, and the Indian coast.

- Another manifestation of climate change—i.e., storm frequency and intensity—may significantly increase these figures in those regions of the world where the storm frequency and intensity increase.

FIGURE 4. IMPACT OF SEA LEVEL RISE ON STORM SURGE RETURN PERIODS



Sea level rise will increase the return period of storm surge events. Note, however, that in countries with low decimating heights, such as Egypt, the frequency of extreme storm surge events will increase more rapidly than in such countries as The Netherlands.

COASTAL ECOSYSTEMS AT LOSS

SPECIFICATION OF METHODOLOGY

As mentioned above, the concept of *loss* is considered to be most appropriate for assessing the vulnerability of ecosystems in the coastal zone, since it indicates the consequences of the impact *with* taking the response into account. Any increases in flooding are not of interest without quantifying the impacts this has on the coastal ecosystem. Furthermore, since it is difficult to quantify changes—e.g. with respect to biodiversity—only (the chance of) habitat area losses are estimated. The response mechanisms taken into account are only limited (mainly horizontal shifts of habitats). Thus, it is more appropriate to interpret the terminology "at loss" as "potentially at loss," since actual future losses may be counteracted by other feedback mechanisms of the physical and biological systems.

In line with the CM, *ecosystems at loss* is defined as the area of special ecological value that is expected to be lost over the indicated time horizon for a variation of the boundary conditions. In effect, the present study compares the vulnerability of the following situations:

- The expected loss of coastal wetlands due to ASLR, without measures and without socioeconomic development.

- The expected loss of coastal wetlands due to ASLR, with measures and without socioeconomic development.

- The expected loss of coastal wetlands due to ASLR, without measures and with socioeconomic development.

- The expected loss of coastal wetlands due to ASLR, with measures and with socioeconomic development.

In summary, the following steps were undertaken to determine the coastal wetlands at loss for the various scenarios:

Step 1 Inventory of special ecological coastal areas (coastal wetlands).

Step 2 Global typology of coasts, based on morphogenesis.

Step 3 Overlay of inventory and typology, classification of response types.

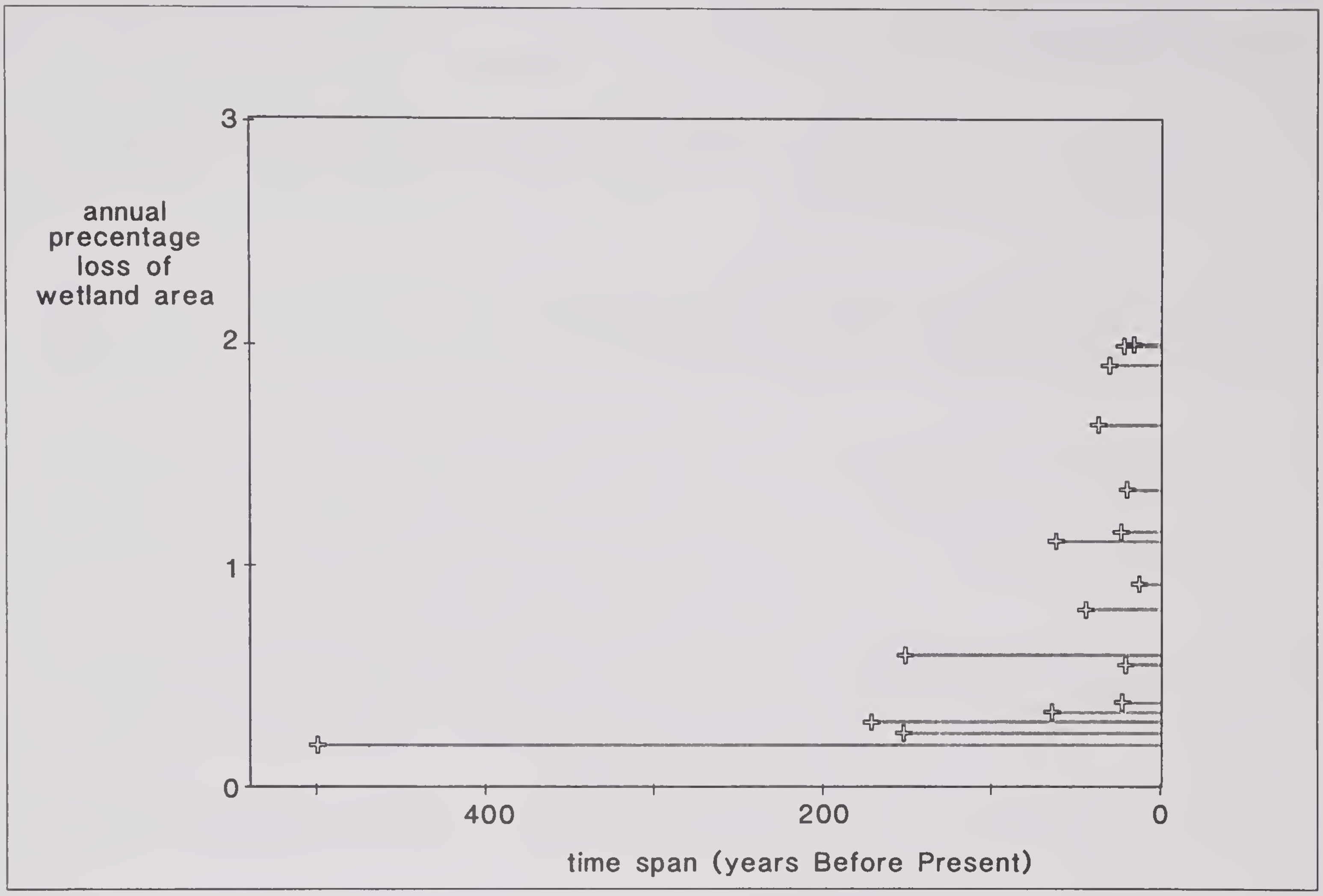
Step 4 Analysis of historic and current trends of wetland loss.

Step 5 Specification of responses according to:
- physical conditions (subsidence, tidal range, etc.) and
- human development factors (population density, river regulation etc.).

Step 6 Estimate of coastal wetland areas at loss.

Each of these steps is discussed in detail in the underlying study report. To give an impression of the historic and present rates of wetland loss, Figure 5 illustrates the documented evidence of wetland loss (see the reference list for sources). As stressed above, the detailed country-by-country results have only limited accuracy and validity. Therefore, aggregated results are presented, but first a discussion of some of the assumptions and associated effects is in order.

FIGURE 5. COASTAL WETLAND LOSS



In the last 100 years, the worldwide loss of coastal wetlands has accelerated precipitously (16 data points from 9 independent references on wetland losses in 11 countries).

SOME ASSUMPTIONS AND THEIR EFFECTS

LIMITATIONS OF DATA SOURCES

There exists a large variety of literature and data bases describing coastal wetlands. Yet, some countries with extensive coastal wetland areas (e.g., Canada) could not be included because of lack of data. Furthermore, the inventoried data sources present the information non-uniformly, and some data sources present contradictory information. These limitations indicate that only conclusions on a regional basis are in order.

COASTAL WETLAND RESPONSE

The causes of coastal wetland decline rates under present conditions are a complicated mix of human-induced and natural causes. To estimate the decline rates on a regional scale, including the additional effect of ASLR, simplifying assumptions had to be made—e.g., mangrove forests on low islands will disappear by definition contrary to those on high islands, and, countries will follow a preservation scenario for the coastal wetlands in those regions where wetlands are declining fast.

AGGREGATED RESULTS FOR COASTAL WETLANDS AT LOSS

- Worldwide, over 900,000 km^2 of coastal area can be classified as "areas of international importance," indicating that their character is in accordance with the criteria set by the RAMSAR Wetlands Convention.

- One-third of the world's wetlands consists of coastal wetlands: salt marshes (15 percent), intertidal areas (10 percent), and mangrove forests (8 percent). While coastal wetlands are recognized to be of high ecological and economic value, they seem to be particularly vulnerable to ASLR.

- Coastal wetlands are being lost at an increasingly rapid rate worldwide (see Figure 5). The increase in loss rates is closely connected with human activities, such as enhanced subsidence and shoreline protection, blocking sediment sources for wetlands, and land development activities.

- An acceleration of sea level rise would increase the rate of net coastal wetland loss. In combination with human activities a 1-meter rise in sea level over the next century would threaten half of the world's coastal wetlands of international importance. In some areas, coastal wetlands could be virtually eliminated, because their ability to migrate inland would be limited over such short time scales. Taking account of increasing human development (the development scenario) will increase this expected loss on the order of 5 to 10 percent.

- Losses of coastal wetlands of international importance are expected to be larger than average for the coasts of the United States, the Mediterranean Sea, the African Atlantic, East Asia, Australian, and Papua New Guinea.

RICE PRODUCTION AT CHANGE

SPECIFICATION OF METHODOLOGY

The concept of *change* is considered to be most appropriate for assessing the vulnerability of agriculture in the coastal zone. With production at change the consequences of increased flooding and other climate change factors on the flood-prone agricultural area are considered in terms of changes in the crop yields. It is assumed that it is not so much the actual loss of agricultural area that is dominant, but rather the production changes due to less favorable hydraulic and climate conditions.

In line with the CM, *rice production at change* is defined as the production quantity that is expected to be lost over the indicated time horizon for the various scenario conditions. However, in the present study a more limited indication is given—i.e., the total production in the area affected by more frequent flooding, with an indication of the order-of-magnitude changes that may occur in this production. These order-of-magnitude changes are based on a simple, hypothetical model that assumes yield changes because of a shift of each crop type toward the next wetter type, due to the "worsening" hydraulic conditions. Because of the limited accuracy of this approach, it is not realistic to specify these order-of-magnitude changes for the various scenarios. Instead a "future" situation is defined without distinguishing any detail in the scenario variables.

In summary, the following steps were undertaken to determine the rice production at loss for the various scenarios:

Step 1 Inventory of mapping of rice production in Asia.

Step 2 Estimate of the production in flood-prone areas.

Step 3 Hypothetical response exercise.

Each of these steps is discussed in detail in the underlying study report. As stressed above, the detailed country-by-country results have only limited accuracy and validity. Therefore, aggregated results are presented, but first a discussion of some of the assumptions and associated effects is in order.

SOME ASSUMPTIONS AND THEIR EFFECTS

LIMITATIONS OF DATA SOURCES

The current production figures, which are based on the literature, have limited accuracy both because of the limited spatial resolution and because of the relatively old production figures (late 1970's).

CROP PRODUCTION RESPONSE

The determination of the response of rice crops to changing conditions requires rather sophisticated approaches—e.g., those used in the context of the analysis of climate change impacts on crops in uniform regions, which combine computer models with actual observations. Therefore, the present approach must be considered to be hypothetical, which is found to produce figures of the same order-of-magnitude as found for some individual regions with the more sophisticated climate change approaches.

AGGREGATED RESULTS FOR RICE PRODUCTION AT CHANGE

Step 1 Approximately 85 percent of the world's rice production takes place in South and Southeast Asia, and of this production about 10 percent is located in areas that are estimated to be vulnerable to ASLR, such that the hydraulic conditions in these areas become less favorable for rice production. The amount of rice cultivated in this area feeds more than 200 million people.

Step 2 Less favorable hydraulic conditions may cause lower rice production yields if no adaptive measures are taken. Especially in the large deltas of Vietnam, Bangladesh, and Myanmar (Burma), serious production reductions may be expected.

Step 3 A simple, hypothetical model indicates that up to 40 percent of the rice production in the areas vulnerable to ASLR may be affected. This could threaten the main food source of 80 million people.

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THE INSURANCE MECHANISM: AN INDUSTRY COMMENT

Andrew F. Dlugolecki
General Accident Fire & Life Assurance
Corporation Limited Plc.
Perth, Scotland

SUMMARY

The insurance industry is experienced in dealing with major property damage impacts arising from natural events. However, the growing scale of these events is causing concern. It is still too early to say what damages global warming may bring but storm risk is identified as a critical hazard, and one that has been related to warmer temperatures in the British Isles. Underlying this is the general increase in economic development and wealth, which accelerates the loss potential.

The proposed Association of Small Island States (AOSIS) insurance pool mechanism goes much farther than traditional insurance, which seeks to maintain the status quo of those suffering losses, and assumes prudent behavior on the part of property owners. Owing to the various practical problems of dealing with underwriting and claims, it is essential to have a local network.

Rather than ignoring the private sector, a more fruitful way to tackle the problem of accelerated sea level rise would be through cooperation, making use of the expertise of the private sector. This trend is already established in mature economies.

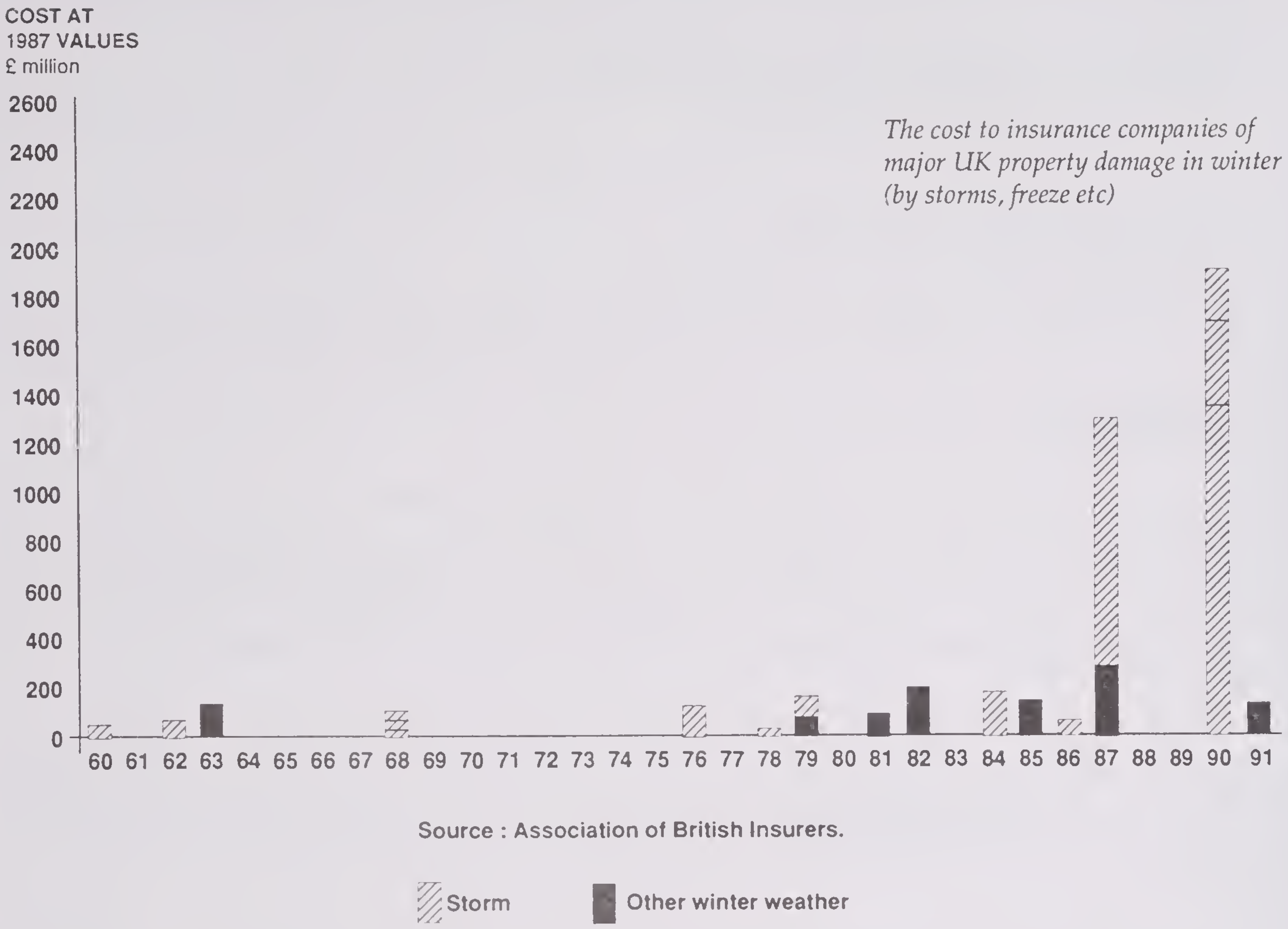
INTRODUCTION

This paper gives a "practitioner's" view of the possibility of a government-funded insurance pool to be used to cope with rising sea level due to global warming (AOSIS, 1991). This is set in the context of the recent experience of the insurance industry with natural weather catastrophes, and current insurance thinking about global warming. Some ways in which the insurance industry could contribute to mitigating the problems associated with global warming and sea level rise outside the proposed pool are also discussed.

INSURANCE AND NATURAL HAZARDS NOW

The insurance industry has been shaken by recent developments, particularly arising from natural hazards. Claims have soared in value and number, even in areas previously thought of as safe, like the United Kingdom. Figure 1 shows how costs have risen by an order of magnitude for storms and prolonged freezing temperatures since 1960 in the United Kingdom.

FIGURE 1. MAJOR U.K. WINTER EVENTS



The cost to insurance companies of major UK property damage in winter (by storms, freeze etc)

Source : Association of British Insurers.

It is clear that the dominant cause of claims is damage from wind storms, which struck in 1987 and repeatedly in 1990. During the period covered by these statistics published by the Association of British Insurers (ABI), there was also a dramatic increase in the cost of drought, through subsidence of buildings. The annual cost now stands at over £500 million. Fortunately, there has not been a recurrence of the disastrous 1953 floods, since these could inflict damage on property alone of perhaps £10 billion (Dlugolecki, 1990).

These patterns are paralleled on a global scale, as is shown in Table 1, drawn from statistics gathered by the reinsurance company Munich Re about major windstorms. In this case, annual statistics are available for uninsured losses, as well as insured claims. Again, the total losses have risen by an order of magnitude since the 1960's, and the insured costs have accelerated even faster. Since the statistics were prepared, the 1991 experience has become available, and it confirms this picture with several severe storms, including Japanese typhoon "Mireille" and Hurricane "Bob."

Non-weather factors have influenced this trend, of course. There has been an increase in the values of property exposed to damage, as economies become wealthier. Urbanization has increased the chance of "big hits." Consumerism has raised the awareness of the usefulness of insurance, and the likelihood that claims will be pursued. Finally, insurers have created larger potential by widening the scope of cover with such measures as index-linking and new-for-old. However, these influences are basically a steady process. Rather, the main influence has been the change in the pattern of natural events, their frequency, severity, and location.

TABLE 1. MAJOR WIND STORMS WORLDWIDE: 1960–90*

Year	No. of Wind Storms/Yr.	Total Damage (billions U.S. $)	Insured Damage (billions U.S. $)
1960	0.8	$2.0	$0.5
1970's	1.3	$2.9	$0.8
1980's	2.9	$3.4	$1.7
1990	4.0	$14.1	$9.8

*Values at 1990 prices.
Source: Munich Re.

The financial impact of damage from natural events on insurance companies can be severe, both for liquidity (as funds are needed rapidly to settle claims) and even for survival. Table 2 illustrates how the rising burden of natural catastrophes has affected capital.

TABLE 2. FINANCIAL IMPLICATIONS OF CHANGING PATTERNS OF NATURAL CATASTROPHE FOR INSURERS

Policyholders	
Property	100% (sum insured or SI)
Risk	110% (including additional costs)
Insurers	
Historical	
Premium	2% (based on SI, covering a package of hazards)
Running Costs	1.8% (expenses + claims)
Catastrophe	0.2% (alternate years)
Underwriting Margin	NIL (2% - 1.8% - 0.2%) in "cat" years
Investment Return	0.2% (on capital and reserves)
Annual Profit	0.2% (NIL + 0.2%) in "cat" years (used for dividend and capital strengthening)
Capital	1.0% (maintained at about 50% of premium)
Present	
Catastrophe	1.0% (in alternate years)
Reinsurance Recovery	0.4% (in "cat" years)
Loss	-0.3% (including reduction in investments income, but with reinsurance recovery)
Capital	0.7% (after one "cat" year)
Future	
Catastrophe	?

Note: These figures are illustrative only. They do not represent any single company, but are meant to be realistic.

Experience has shown that the relationship of weather-to-cost is exponential, not straight-line. This applies to freezes, droughts, floods, and storms. Even a 5-mph increase in wind speed can double the cost of storm damage. The loss rate in the worst-hit areas in England in 1987 came to 1 percent of the value of the insured property, although 50 percent of the dwellings were damaged to some degree. With the greater severity of tropical hurricanes, loss rates in excess of 10 percent occurred with "Gilbert" in 1988 and "Hugo" in 1989. Coastal areas are particularly vulnerable due to the possible combination of tides, storm surge, and wave action. Also, many regions present further natural hazards by way of earthquakes and volcanoes.

With this background, it is understandable that the insurance industry is wary of further commitments with regard to coverage for damage from sea level rise. Yet governments are moving in that direction. In 1961, insurers in the United Kingdom extended their coverage to include floods, because of political intervention, and French governments have pursued an even broader policymaking insurance cover against natural catastrophes available to policyholders.

The insurance industry uses four classic approaches for dealing with profitability problems:

1. Limit the risk through use of deductibles and selective underwriting. However, governments favor wide coverage, so this may not be practical.

2. Control damage by tightening up claims procedures. For example, use company-recommended repairers only and 24-hour free phone lines for quick claims reporting.

3. Transfer the risk to reinsurers. But they have also become aware of the immense catastrophe potential, with the result that reinsurance is much more expensive, and not so much is available either.

4. Price the product by increasing premiums to reflect the greater hazards present. This is happening, but not fast enough because insurers don't wish to lose market share, and hope that "it won't happen again."

At the same time, the industry is also beset with other problems—crime, consumerism, and recession, to name but three—all of which put pressure on profit margins, and distract resources from the issue of natural hazards.

TRENDS IN STORMINESS AND TEMPERATURE

As yet there are no clear global trends in reported storminess over a long period. Although Table 1 suggests an increase, and this is supported by Figure 1, a 30-year period is too short for meaningful analysis. However, combining data relating to storms (Lamb, 1991) with temperature (Dlugolecki,1990) results in a positive correlation between winter storms and winter warmth was for the period 1690–89 for the British Isles. Table 3 shows that the frequency of storms in "warm" winter months is 15 percent, as compared with less than half that level in "medium" or "cool" months. This result is significant at the 0.5 percent level. There is also some suggestion that "cool" storms have a reduced strength. This pattern was dramatically confirmed by the severe storms of January and February 1990, both of which were "warm" months.

What is disturbing for insurers is that there has been a definite trend toward warmer extremes since the 1960's, which parallels perfectly the acceleration in costs. Patterns in other regions of the world are still uncertain, because observations are not so well established, but there is clearly a case for further work in this area.

TABLE 3. WINTER STORMS AND TEMPERATURE

Type of Winter Month	Storm Frequency (%)	Storm Strength (Lamb Units)
Warm	15	2,568
Medium	7	2,544
Cool	6	1,075

"Warm" and "cool" months are defined as lying in the upper or lower deciles of monthly average temperatures for Central England during 1659–1988 for the individual calendar months December, January, and February. Storm occurrence dates and strengths are derived from Lamb (1991), as amended in Dlugolecki (1991).

CURRENT INSURANCE THINKING ABOUT GLOBAL WARMING

Despite the high level of debate about global warming, and the likely repercussions for property damage, there has been little written outside the insurance industry about how insurance might be affected or how it might help mitigate the harmful effects. One honorable exception is the United Kingdom study on global warming, which devoted one chapter to the financial sector (CCIRG, 1991). The main conclusions for insurance are:

1. There is an information gap. We need to know the future pattern of natural hazards in detail.

2. If the patterns can be foreseen as far ahead as IPCC climate projections, then insurers should be able to react, because most contracts of insurance are only 12 months long. However, this is somewhat academic, given the current severe problems that insurers are having with recent shifts in weather patterns.

3. In many cases, long-term assets are financed with the "underpin" of an insurance policy to protect against the financial repercussions of physical loss or damages. Thus, action within a shorter time frame by insurers could leave a hole in the project security.

4. As well as implications for property insurance, global warming also could affect nonproperty classes, like liability and health insurance.

5. Market trends will exacerbate cost increases through factors like wider cover, dishonest claimants, and rising wealth.

6. Claim-handling systems will need to be robust to deal with sudden "deluges." To a great extent, this has already happened. Whereas one million storm claims overwhelmed United Kingdom insurers in 1987, they coped with three million in 1990 quite effectively.

7. Political pressure for the private insurance market to handle the financial impact will continue, reducing the burden on public funds.

8. The insurance industry will become more interested in risk management. Three areas look very worthwhile: sea defenses, owing to the huge coastal exposure to floods; construction standards, as the worst claims occur when buildings are poorly constructed, despite adequate design; and tree management, because of the problems of tree fall and root invasion.

9. Events overseas could be critical for international insurers; it is not just a domestic issue.

10. Fiscal changes are necessary so that insurers can deal with the uneven occurrence of catastrophes by building up reserves in advance.

Further papers can be found in the series of conferences held by the Insurance and Reinsurance Research Group and its successor DYP (IRRG, 1988–92).

THE NATURE OF INSURANCES

The fundamental principle of insurance is that "the many pay the few." That is, a fund collected from the many in advance is distributed to meet the losses of the few. The intention of the insurance contract is to restore the status quo. It is assumed that the proposer will behave prudently. This includes taking reasonable steps to avoid or reduce losses. This section considers the main processes of insurance, the format of the contract of insurance, and some practical problems.

MAIN PROCESSES

The two main processes in the insurance industry are underwriting (accepting risks) and claim handling. As Figure 2 shows, underwriting is akin to the process of handling an agricultural commodity, starting from crops in the field and then harvesting, storing, and blending them. The "proposer" wishes to insure his "untreated," single risk. After risk management, this is brought to an insurable state, and is often negotiated via an agent or broker and placed with an insurer who administers the contract of insurance. The insurer will have a variety of risks and may have insisted that the proposer retain some of the risk as a deductible so that he maintains a stake in avoiding losses. By a further process of negotiation, the insurer may transfer some of the risk to a reinsurer, with an even wider spread of risks.

Figure 3 shows the various steps in settling claims. There are several important features. First, the claim is compared with the contract of insurance. Second, often the site of the damage is visited by an adjuster to quantify the loss. And third, the repairer is intimately involved in carrying out the agreed course of action, with due controls. In other words, it is not simply a matter of passing over money to claimants on demand.

THE FORMAT OF THE INSURANCE CONTRACT

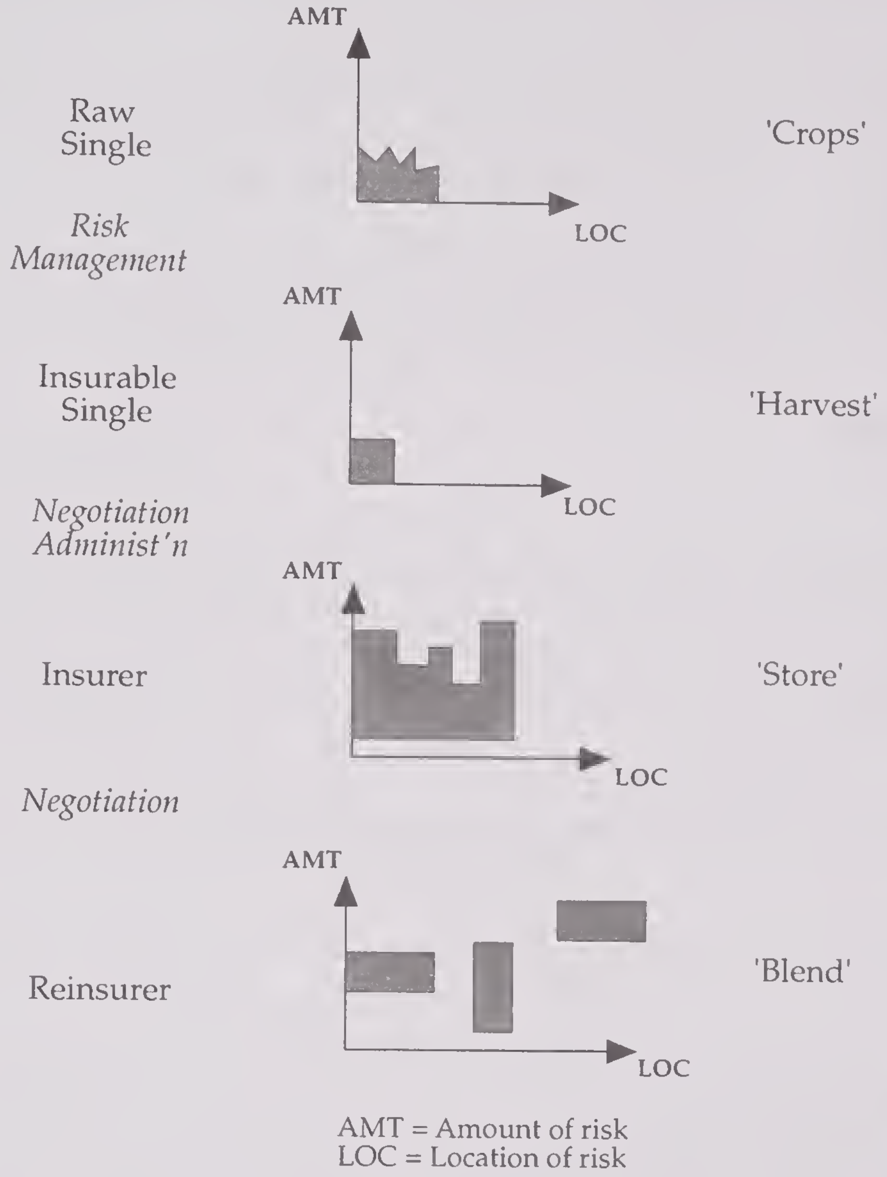
The contract is stated in a written document—the policy. It promises: *compensation* within specified financial limits, or by replacement for *loss* or damage by specific unintended *events* during a time frame to *property* owned by the proposer and duly specified and quantified in return for a *premium* reflecting the risk and paid to the claims fund.

PRACTICAL ASPECTS OF INSURANCE

One natural problem is *selection*—i.e., only those at high risk will insure, so that the fund will not be sufficient to meet the claims. This can be solved in the free market by underwriting and marketing, or by regulation if government intervenes to make cover compulsory.

Attitude to risk may deteriorate, in that the availability of insurance may encourage imprudent (risky) behavior—e.g., building on floodplains. Here again underwriting is essential, with firm claims control, but obviously planning regulation may avert the difficulty.

FIGURE 2. ACCEPTING RISK



A comparison between insuring risks (left hand of diagram) and handling commodities (right hand).

Fraud is a growing problem, with many claimants exaggerating their losses or even inventing them. Therefore, firm claims control is essential. Related to this is *underinsurance*, where the proposer may understate his values perhaps to reduce his contribution to the fund.

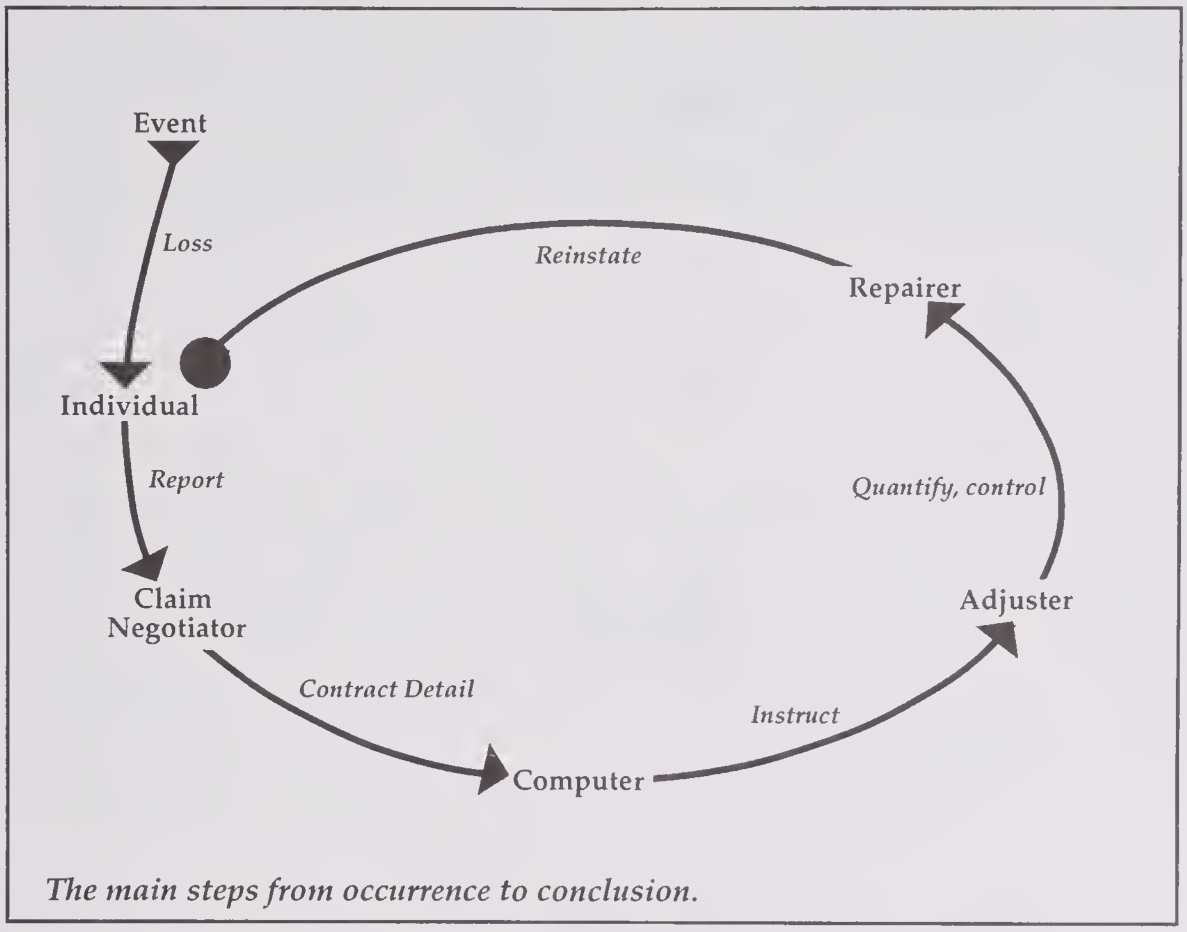
Delays in reporting claims can also cause problems in that damage can deteriorate, or further similar incidents can occur. On occasion, claimants may delay intentionally to try to ensure that a higher level of coverage is in force before seeking compensation.

A rating structure is required to translate the degree of hazard at each property into a premium that is a fair reflection of the relative potential for loss, together with the costs of administration. In view of the random occurrence of claims and the individual nature of each property, any rating structure can only be an approximation.

Gradual causes of damage are not usually insurable because of the difficulty of deciding which period the losses happened. If such hazards are to be included, it is usually on a "claims made" basis—i.e., the contract covers claims reported in the period, rather than occurring in the period.

These problems show that unfortunately insurance cannot operate without adequate control mechanisms, since any financial system can bring out the worst in human nature.

FIGURE 3. SETTLING CLAIMS



The main steps from occurrence to conclusion.

THE AOSIS PROPOSAL FOR AN INTERNATIONAL INSURANCE POOL

Details of this proposal are available in the working documents of the IPCC Subgroup on Coastal Zone Management (AOSIS, 1991). Briefly, the proposal envisages that developed economies would contribute funds to a pool that would compensate members of AOSIS who have suffered damage from accelerated sea level rise. Claims would not be eligible unless sea level reached a specified height and/or rate of rise. The damage would include noneconomic losses and foregone opportunities for economic development as well as monetary losses, but would exclude privately insured losses. In all cases, values would be agreed in advance for the potential at risk.

Further details of the valuation approach are given in another paper (IPCC, 1991). While it is still in draft form, a number of critical observations can be made under the heading of General Principles, Funding, Format of the Contract, and Practical Aspects.

GENERAL PRINCIPLES

As currently comprised, the pool would go beyond restoring the status quo for AOSIS members. It also proposes that coastal development that took place within the past 30 years would be recompensable, without any consideration of whether such development was prudent. In both respects, therefore, the proposal goes beyond pure insurance.

FUNDING

Without a quantified assessment of the likely costs of sea level rise, it is unlikely that the pool would proceed, even with an annual limit. Also, because the pool is "high risk," there must be a high chance of exhausting it in particular years, with consequent delays.

The pool will have to compete for funds with other deserving causes—e.g., similar disasters in more populous nations like Bangladesh; nonclimate-related disasters (earthquakes, volcanoes); and "first-world" problems with enormous costs (pollution, drugs).

The fact that the beneficiaries of the fund are not required to contribute to it weakens their interest in loss prevention, but it could be overcome by introducing some form of "token" premium payments, assuming that a rating structure can be agreed on.

FORMAT OF THE CONTRACT

Here again, there are certain noticeable differences from the standard. *Losses* are defined to include the costs of accommodating accelerated sea level rise, even when this would simply be prudent behavior. Private-sector insurance losses are excluded, which is bound to make the public less likely to take such cover, and will also give rise to differing standards of compensation in the event of a catastrophe.

The *event* is defined as accelerated sea level rise, but in fact much of the coastal damage will relate to specific incidents—e.g., storms, rather than permanent inundation.

It will be unclear whether such costs relate to accelerated sea level rise, climate change, or indeed just "normal" losses from perennial tropical cyclones.

Property is defined to include hypothetical losses (the value of foregone developments, which might not have happened, or might have been imprudent). Also, the valuation of noneconomic losses (ecology, human lives) will be problematic. For some of these classes of property, it is not clear to whom the *compensation* will be paid or how it will be used to reestablish the status quo.

PRACTICAL ASPECTS

Two points are worth noting, related to the two main insurance processes of underwriting and claim-handling. First, it will be difficult to arrive at a uniform and fair rating structure for a widely scattered group of nations with different cultures, infrastructures, and information about their hazards. Second, ensuring physical reinstatement and allocation of monetary compensation requires a local distribution system.

COOPERATION WITH "PRIVATE" INSURANCE

Because of the various problems facing the proposed pool, it may be worth considering whether accelerated sea level rise could be alleviated with the assistance of private insurance, rather than ignoring it. Right away it has to be said that because of the high-risk/low-wealth profile, private insurers would certainly not find it attractive to operate in this sector without financial support from some form of pool funded internationally.

Encouraging a "private" sector has the advantage that insurance can tackle a variety of other hazards (e.g., fire), and provides a distribution network that can be used in the recovery phase of disaster management. There are precedents for insurers to be indemnified for claim payments from a public fund (e.g., terrorist damage in Northern Ireland). The integration of private insurance into the system for disaster management would thus be able to efficiently handle the type of losses where insurance is appropriate—moderate to large property damage—leaving public agencies to handle other impacts. Allowing the private insurer to vary the premium it charges according to the risk would encourage proposers to make improvements to their property to reduce costs. Here again, insurers are accustomed to provide advice on risk management in their service. An alternative variation in New Zealand has the private insurer collect a premium and administer claims on behalf of the public fund; this arrangement covers earthquake and war damage.

If a reasonable level of information is gathered about property at risk, with a first level of financial compensation through a public fund and an efficient network to handle claims, it may also be possible to reinsure part of the fund's liability in the international private reinsurance market. This would increase the "capacity" of the pool to meet disasters and also would give access to the expertise that this market has developed in tackling major hazards (e.g., in rating structures, fund management).

Where a country requires assistance in setting up an insurance industry, or reinforcing it, then the institutions in mature economies could surely provide assistance, advice, and training. In the United Kingdom, the relevant bodies are the Association of British Insurers on "commercial" matters, the Department of Trade and Industry on regulation, and the Chartered Institute of Insurance on training.

The above proposals to use private insurance are not novel, as can be seen from various examples, and the trend in Europe is certainly in this direction. The question is whether private insurers can provide their services and make a profit. If not, can the public sector adapt private-sector mechanisms to handle the problems in a nonprofit-making way.

Note: The views presented in this paper are those of the author alone, and not necessarily those of any organization with which he is associated.

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EXPECTED RESPONSES OF CARIBBEAN CORAL REEFS TO DISTURBANCES CAUSED BY SEA LEVEL RISE

Vance P. Vicente
U.S. Fish and Wildlife Service
Caribbean Field Office
Boqueron, Puerto Rico

INTRODUCTION

Sublittoral systems (coral reefs, sea grass beds, mangrove root communities, mud bottoms, etc.) are exposed to four different factors that operate in different scales of time, space, and intensity:

1. Long-term historical natural processes, such as changes in sea level and in sea surface temperatures.

2. Ecologically deterministic factors which modify systems within ecological time scales.

3. Stochastic or density-independent factors that happen in short-time intervals, but that often have catastrophic effects on system components, yet may also enhance local diversity at intermediate levels (sensu Connell, 1978) of intensity and frequency (e.g., hurricanes).

4. Anthropogenic sources of disturbance (e.g., point and nonpoint source pollution).

Often these factors interact synergistically or operate simultaneously on a system. They are discussed in relation to coral reef systems to allow prediction as to how these systems may react to different scenarios of sea level rise.

Because of their geographically enclosed nature, relative small size, and proximity to continental masses, Pleistocenic glaciations have affected Caribbean reefs and often have become destroyed. For example, Lighty et al. (1978) explain that the cause of the massive mortality of a barrier reef (about 100 km long) along the southeast submerged coast of Florida corresponds to sea level rise during the Holocene transgression about 7,000 years ago. Similar mortalities have been found in other localities of the Caribbean (e.g., St. Croix). In most cases, the dead reefs consisted of *Acropora palmata* or elkhorn coral. The genus *Acropora* is the fastest-growing hermatypic coral in the Caribbean, and at the time, had a maximum sustained growth of 15.2 mm/year. Yet, these reefs apparently could not cope with disturbances (e.g., erosion and turbidity) associated with sea level changes.

On the other hand extant reefs can achieve considerable vertical accretion rates and can *potentially* keep pace with expected increments in sea level. For example, Stearn and Scoffin (1977) and Stearn et al. (1977) estimated that a rapidly growing reef community in the Caribbean (Barbados) produced 15 kg $CaCO_3$ m^2 yr^1, which is equivalent to a vertical accretion rate of approximately 11 mm/yr. Buddemeier and Smith (1988) summarized existing data on vertical coral reef accretion from different parts of the world and concluded that the best estimate of maximum sustained growth by a coral reef is 10 mm/year, which is in fact the typical linear growth rate of individual massive corals worldwide. In the same year, Hendry (1988) confirms that high coral reef growth rates of 12-15 mm/year have been registered for Caribbean reefs during the Holocene, and concluded that Caribbean reefs can keep pace with an expected sea level rise of 5.3 mm/yr.

This paper evaluates how *present-day* Caribbean reefs might respond to sea level rise from an ecological perspective.

OBSERVATIONS

Caribbean coral reefs are developing under conditions that are not necessarily optimal for growth, in contrast to coral reefs within the IndoPacific region. Coral reefs develop in the Caribbean in rather peculiar conditions, and major events made them more susceptible to climate changes than similar systems in other regions.

Caribbean reefs receive allochtonous sources of nutrients and sediments from five major rivers: Mississippi River (North America), Río Grande (Mexico), Río Magdalena (Colombia), Río Amazonas (Brazil), and Río Orinoco (Venezuela). The Amazon and Orinoco Rivers are known to inhibit or reduce coral reef development and coral diversity in the inner-sublittoral coast of South America, including offshore islands (e.g., Trinidad-Tobago). Furthermore, these two rivers are known to influence significantly the tropical surface water throughout the Antilles. (The tropical surface water is the water mass within which coral reefs develop.)

Coral reefs develop best in oligotrophic conditions, where primary productivity is low. This is not the case of the Caribbean Sea, where according to Koblentz-Mishke et al. (1970), marine primary productivity is relatively high (100 - >500 mgC m^2 day^1), due in part to nutrient enrichment, as discussed by Highsmith (1980).

The proportion of hermatypic (reef builders bearing zooxanthellae) corals containing boring bivalves per coral head is higher in Caribbean reefs than in coral reefs in the Indian Ocean and in the western Pacific region (Highsmith, 1980). Loss of skeletal mass by bioerosion obviously reduces reef growth.

The occurrence of boring sponges (clionids) in Caribbean corals is also very high. In fact, encrusting spirastrellid sponges can cover and kill live coral surfaces and at the same time dissolve coral surfaces (Vicente, 1978).

Caribbean massive hermatypic corals have more of their skeletal surface exposed to bioerosion and, therefore, have less live (growing) coral surface than individual IndoPacific corals. These characteristics make Caribbean corals more prone to become dislodged by storms and hurricanes (Highsmith, 1980).

Live Caribbean corals are very prone to become displaced competitively by macroalgae. A massive die-off of the black urchin *Diadema antillarum* (a major herbivore of coral reef systems) occurred within practically the whole Caribbean region (Lessios et al., 1984; Vicente and Goenaga, 1984). Consequently, macroalgael have increased dramatically in many places, displacing corals in Puerto Rico (Vicente, 1987), adjacent islands, Jamaica, and other localities (Hughes et al., 1987).

Furthermore, the fishing of coral reef herbivorous fish, such as the Parrot fish (*Sparisoma* spp.), has increased. This also may account for observed increases in algal biomass. These observations are supported by the work of Hughes et al. (1987) in Jamaica.

Caribbean corals are under intense competition for space by other sessile components. For example, Caribbean sponge biomass is five to six times greater than that of the Pacific (Wilkinson, 1987). Furthermore, defensive mechanisms of Caribbean corals (e.g., extracoelenteric digestion, production of sweeper tentacles, or allelochemicals and morphological adaptations) are not effective against common encrusting sponges, which frequently overgrow and kill them (Vicente, 1990a).

Biological diversity is lower in the Caribbean region when compared to the IndoPacific. For example, there are 75 percent more genera and 85 percent more species of corals in the Pacific than in the Caribbean (Wilkinson, 1987), suggesting a lower system stability.

A large portion of the Caribbean lies within the hurricane belt and, therefore, is frequently exposed to severe hurricane-related impacts. The importance of hurricanes in enhancing local coral diversity (sensu Connell, 1978) has not been demonstrated yet for the Caribbean. The severe disruption of Caribbean reefs has been well documented (see, for example, Woodley et al., 1981). The severe impacts of Hurricanes "Gilbert" and "Hugo" in 1989 have been well established. The greater susceptibility of corals to storms has been suggested (Highsmith, 1980).

Caribbean corals have recently been exposed to episodic bleaching events (Williams et al., 1987; Goenaga et al., 1989). Bleaching of live coral tissue can have temporary or permanent negative effects on coral growth.

Caribbean corals are affected by various forms of disease and stresses (e.g., black band disease, white band disease, shutdown reaction, stress-related necrosis, epidermal cell hyperplasia, tissue change necrosis associated with sedimentation and algal interactions, *Nematopsis sp*. spores, Coccidean spores, unidentified microparasites (ciliates and amoebas), and coral neoplasia). These forms of coral disturbance are discussed and reviewed by Peters (1984).

Some reef taxa (e.g., commercial sponges of the genus *Spongia* and *Hippospongia*) appear to have become either extinct or rare in various islands of the Caribbean. These extinctions appear to be related to positive thermal anomalies in sea surface temperature (Vicente, 1990b). Other species that have migrated into tropical reef systems and that evolved in subtropical or temperate systems are more likely to become locally extinct by climate changes (e.g., increase in SST) than eutropical species.

CONCLUSION

Many extant Caribbean reefs are not developing under optimal ecological conditions. In fact, many reefs are already "dead" (0 percent coral cover) and will not exhibit any significant growth in the next decades. Furthermore, many reefs have lost their ecological integrity and, therefore, will exert functions other than those typical of coral reefs.

The future of extant coral reefs in the Caribbean is dim when we further take into consideration anthropogenic factors. Nonpoint source pollution has caused the destruction or loss of integrity of many coral reefs, in particular *fringing* coral reefs. Fringing coral reefs develop next to island or continental shores and, therefore, are more susceptible to sediment runoff and eutrophication from land-based sources. Sediment runoff and eutrophication increase algal overgrowth and enhance bioerosion, which impede vertical growth.

Many studies have been and are being conducted on Caribbean reefs. However, there is a strong need to synthesize existing information in order to make it useful for managers.

The Caribbean Fisheries Management Council is taking the necessary administrative steps to sponsor a wider Caribbean conference in 1993 on the status of Caribbean reefs. Percent coral cover data (the best index of present reef growth) from coral reefs under different ecological regimes will be provided. Once this information becomes available, we can more reliably predict how coral reefs will respond to sea level changes.

RECOMMENDATIONS

Coral reefs are natural, self-accreting sea walls that, among other functions, protect the shoreline from disturbances associated with sea level rise. Other marine systems are as important in protecting the shoreline. Salt marshes in temperate latitudes, mangrove forests in tropical and subtropical latitudes, and sea grass beds in all latitudes (except at the poles) stabilize unconsolidated sediments, resist erosion, and, in fact, grow vertically with sea level rise. Many of these systems have done so for over 7,000 years. Restoring, enhancing, and creating such systems, particularly in areas of high vulnerability, can help mitigate the impacts of sea level rise.

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IMPACTS OF SEA LEVEL RISE ON PACIFIC ISLAND MANGROVE SWAMPS

*Joanna C. Ellison**
Department of Geography
University of California at Berkeley
Berkeley, California

ABSTRACT

There are two main environmental settings for mangroves of the Pacific: (1) deltaic and estuarine mangroves of high islands and (2) embayment, lagoon, and reef flat mangroves of low islands. It is indicated from past analogues that their close relationship with sea level height renders these mangrove swamps particularly vulnerable to disruption by sea level rise. Stratigraphic records of Pacific island mangrove ecosystems during sea level changes of the Holocene show that low-island mangroves could keep up with a sea level rise of up to 8-9 cm/100 years, but at rates of over 12 cm/100 years could not persist. This is shown by paleoecological reconstruction of mangrove response to sea level rise in Tonga. Mangroves of high islands can keep up with rates of sea level rise of up to 20 cm/100 years, according to the amount of fluvial allochthonous sediment input.

Sea level rise may cause low cliff erosion of mangrove sediments at the seaward edge, sheet erosion of surface sediments and litter, and widening of creek banks and estuary mouths. This loss of litter will affect faunal food chains. Increased inundation and salinity may cause stress symptoms in mangrove species, such as reduced growth, reduced litter production, and reduced resistance to pests and storms.

Monitoring for these impacts should be carried out, including substrate elevation relative to the tidal prism, sedimentation, litter fall and surface retention, as well as changes in the growth and spatial extent of different species. This is the aim of the UNEP-IOC-WMO-IUCN long-term global monitoring system of mangroves and coral reefs, which is presently being established.

INTRODUCTION

The term *mangrove* is used to describe a taxonomically diverse group of tree species that grow in the upper intertidal zone of sheltered shores in the tropics. The extent of their cover has been estimated by the International Tropical Timber Organization to be 20 million hectares. Adaptations developed for their saline wetland environment, such as aerial roots, halophytic strategies, and vivipary, distinguish mangrove trees as a specialized minority within their families (Hadac, 1976). There are 34 true mangrove species in nine families, each with a limited geographical distribution around two centers of diversity—Indo-Malaya and Central America (Tomlinson, 1986). Mangrove species of the Pacific are of the Indo-Malayan assemblage, and decline in diversity from west to east across the Pacific, reaching a limit at Samoa. To the east of Samoa there are no mangroves, owing to isolation. The Pacific islands in Table 1 are listed from west to east, and the area of mangroves and number of species indicate this trend.

TABLE 1. PACIFIC MANGROVES

Country Island	Km^2	Physiography	No. Species
Australia	11,617 [b]	Continental	28
Papua New Guinea	6,000 [b]	Continental	30 [f]
Palau	47 [d]	High	10 [f]
Micronesia	86 [d]	High	
Guam			7 [f]
Saipan			2 [f]
Truk			7 [f]
Ponape			7 [f]
Kusaie			7 [f]
Solomon Islands	642 [c]	High	19 [f]
Vanuatu		High	11 [f]
New Caledonia	200 [c]	High	11 [f]
Nauru	0.02 [c]	High	1 [f]
New Zealand	198 [b]	Continental	1[f]
Marshall Islands		Low	4 [f]
Kiribati		Low	4 [f]
Tuvalu		Low	2 [f]
Fiji	197 [b]	High	7 [f]
Viti Levu			
Vanua Levu			
Tonga	10 [c]	Low	7 [f]
Tongatapu			
Vava'u			
Western Samoa		High	7 [f]
American Samoa	0.5 [e]	High	7 [f]
Tutuila			
Kermadec	0		0
Niue	0		0
Hawaii		High	2 [a]
Cook Islands	0	High	0
Tokelau	0		0
Phoenix	0		0
French Polynesia			1 [a]
Tahiti			
Moorea			
Bora Bora			

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[a] Introduced.

[b] World Resources 1991-92.

[c] World Resources 1986.

[d] Miyagi & Fujimoto, 1989.

[e] Whistler, 1976.

[f] Woodroffe, 1987.

The importance of mangrove ecosystems is well established as: sediment traps promoting aggradation and maintaining the quality of coastal waters, natural breakwaters protecting coastlines from erosion during storms, a natural resource base for silviculture and a large range of economic products, habitats for rare fauna, and nurseries for commercially valuable fish and crustacean species, as well as for educational and tourism uses. These attributes are described in detail by Chapman (1976), Hamilton and Snedaker (1984), and Tomlinson (1986).

Large mangrove ecosystems develop on sedimentary shorelines of gentle gradient, between mean sea level and the level of mean high-water spring tides (Lear and Turner, 1977; Belperio, 1979). Growing in the upper half of the tidal range, their close relationship with sea level position renders mangrove swamps particularly vulnerable to disruption by sea level rise. With most Pacific islands having a tidal range of less than 1 meter, mangrove ecosystems will be disrupted by a sea level rise of 0.3 meters, and will retreat landward with a sea level rise of 1 meter. However, such factors as physiographic location, tidal range, species assemblage, and sediment supply contribute to the heterogeneity of mangrove responses to rising sea level, investigated in this paper.

Research to investigate the impacts of sea level rise on mangroves falls into two areas. First, sea level effects on an ecosystem can be reconstructed from the past, from analysis of stratigraphy, provided the evidence is available from proxy indicators. This technique has the advantage of indicating long-term complex system responses, though detail of short-term individual responses of species can usually only be speculated. Second, present-day case studies can be examined, such as areas of the world where sea level is rising or areas where mangroves have been flooded to control mosquitoes.

PAST RECORDS OF MANGROVE RESPONSES TO SEA LEVEL RISE

Within the intertidal habitat of mangroves, species have different preferences of elevation, salinity, and frequency of inundation, resulting in species zones. Substrate elevation can be increased under mangroves, by accumulation of vegetative detritus to form a mangrove peat or mud, which may also contain matter brought in by the tides and by rivers. If the sedimentation rate keeps pace with rising sea level, then the salinity and frequency of inundation preferences of mangrove species zones will remain largely unaffected. However, if the rate of sea level rise exceeds the rate of sedimentation, then mangrove species zones will migrate inland to their preferred elevation, and seaward margins will die back. Thus, to assess the vulnerability of mangroves to sea level rise, the rate of sedimentation must be established from studies of Holocene stratigraphy.

Stratigraphy of Pacific island mangroves indicates that mangroves have only become established in expansive swamps since the middle of the Holocene, about 6500 years before the present. Before this time, they were limited by the interactive factors of rapid sea level rise and the lack of sedimentary shorelines. Mangroves probably survived this period as individual trees, as seen today on shorelines with too steep a gradient or that are too exposed for expansive swamp development.

There are two major environmental settings for mangroves of the Pacific: (1) deltaic and estuarine mangroves of high islands and (2) embayment, lagoon, and reef flat mangroves of low islands. These are assessed for their relative vulnerability to sea level rise.

DELTAIC AND ESTUARINE MANGROVES OF HIGH ISLANDS

Deltaic and estuarine mangroves occur on islands sufficiently high to develop a river system and so deliver significant quantities of sediment to the coastal zone. These areas are the most extensive mangroves of the Pacific islands—for example, the Rewa Delta, Viti Levu, the Dumbéa Delta, New Caledonia, and the estuaries of Palau and Ponape. The mangrove areas receive terrigenous sediment from the island and also accumulate vegetative debris to form a mud.

Table 2 indicates the rate of sediment accretion from deltaic and estuarine mangroves of high islands. From studies on Viti Levu and Lakeba, Fiji, and Kosrae, Caroline Islands sediment accumulation rates of up to 19 cm/100 years are recorded. These are reviewed in detail by Ellison and Stoddart (1991). In conditions of stable sea level or slow sea level rise, the high sediment supply to these mangrove areas enables the seaward migration of the mangrove area and the conversion of landward mangroves into freshwater swamps or marshes.

TABLE 2. RATES OF MANGROVE PEAT ACCRETION

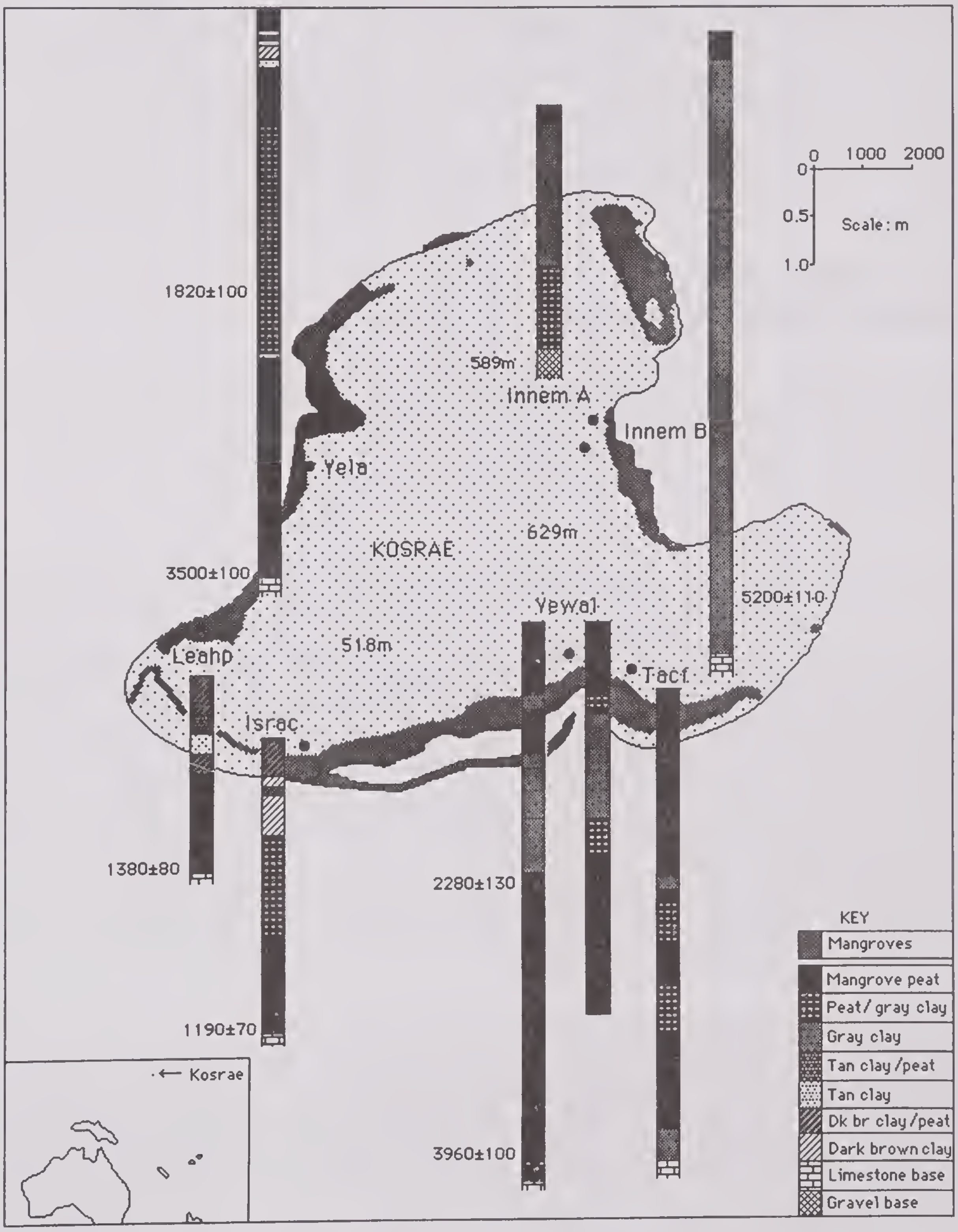
Location (Source)	**Rate of Accretion (cm/ 100 years)**
Low Islands	
Tongatapu	
(Ellison, 1989)	7.7
Grand Cayman	
(Woodroffe, 1981)	8.8–9.0
Bermuda	10.6
(Ellison, in press)	
High Islands	
Fiji	
(Southern, 1986)	11.7
(Matsushima, et al., 1984)	7.6
(Latham, 1979)	13.1
Caroline Islands	
(Ward, 1988)	13.4–14.0
(Matsumoto, et al., 1986)	13.7
(Bloom, 1970)	3.0
Samoa	
(Matsushima, et al., 1984)	9.9–10.5
(Bloom, 1980)	18.8

Source: Ellison & Stoddart, 1991.

In the Caroline Islands, Bloom (1970) showed from 100 cores on the volcanic islands of Truk, Pohnpei (Ponape), and Kosrae (Kusaie) a 6.2-meter accumulation of sediments in the last 6500 years. Between 6500 and 4100 years before present (B.P.) these sediments are estuarine muds, accumulating at 25.3 cm/100 years. Material dated to 4100 B.P. then shows widespread conversion of open, sandy bays at W. Moen, Truk, to fresh/brackish-water swamps, and the subsequent accumulation of freshwater peat at 3.0 cm/100 years.

At Rohi, S.E. Ponape, Matsumo et al. (1986) found mangrove peat of up to 4 meters in depth, where a date of 4790±220 B.P. showed the time of conversion of low-tide reef flats to mangrove swamps when the rate of sea level rise was slowing. Mangrove peat accumulation then kept up with rising sea level, at a maximum rate of 13.7 cm/100 years. The same pattern is shown from Kosrae in the Eastern Carolines by Ward (1988), who found rapid accumulation of peat-dominated sediment in the last 4000 years, shown in Figure 1. At Yewal, peat was found between depths of 5.7 and 2.6 meters, giving respective dates of 3690±100 and 2280±130 B.P., an accumulation rate of 14.8 cm/100 years. At Yela, peat was found between 5.8 and 3.0 meters, giving respective dates of 3500±100 and 1820±100 B.P., and an accumulation rate of 13.4-14.0 cm/100 years.

FIGURE 1. COASTAL STRATIGRAPHY OF KOSRAE, CAROLINE ISLANDS



Core depths indicate rapid sedimentation rates on this high island. Data from Ward (1988).

In Fiji at Melimeli Delta, Southern (1986) found peat to 1.8 meters deep, dated to 1630±250 B.P., giving an accumulation rate of 12 cm/100 years B.P. Pollen study of this basal level showed a domination by mangrove taxa, such as *Bruguiera* and *Rhizophora*. Matsushima et al. (1984) cored a mangrove delta at Kalokolevu, also on the south coast of Viti Levu, finding silty humus to a depth of 2.25 meters. A date of 2640±140 B.P. at 2.10 meters deep in the core gives a subsequent accumulation rate of 7.6 cm/100 years.

At Levuka, a restricted swamp on the southwest coast of Lakeba, Fiji, Latham (1979) found organic sediment with 25 percent organic matter above an organic clay. A date of 940±120 B.P. at 1.2 meters in depth gives a subsequent accumulation rate of 13.1 cm/100 years. A loose coral sample from beneath the peat gave a date of 4470±155, taken as evidence for expansion of mangroves over reef flat areas since that time (McLean, 1979).

At the Pururi delta area of the Gulf of Papua, P.N.G., a large mangrove system is actively accreting at the present time, and Pernetta and Osborne (1988) suggest that with sea level rise the area will be largely unaffected, owing to high sediment supply. However, in contrast, the Kikori section of the Gulf of Papua has tidally dominated estuaries that are dependent on long-shore drift of sediment for maintenance of coastal stability. A increased rate of sea level rise may result in decreased quantities of sediment transported by longshore drift to the Kikori area, so leading to recession of the coastline and reduction in the extent of mangroves (Pernetta and Elder, 1990).

EMBAYMENT, HARBOR, AND LAGOON MANGROVES OF LOW ISLANDS

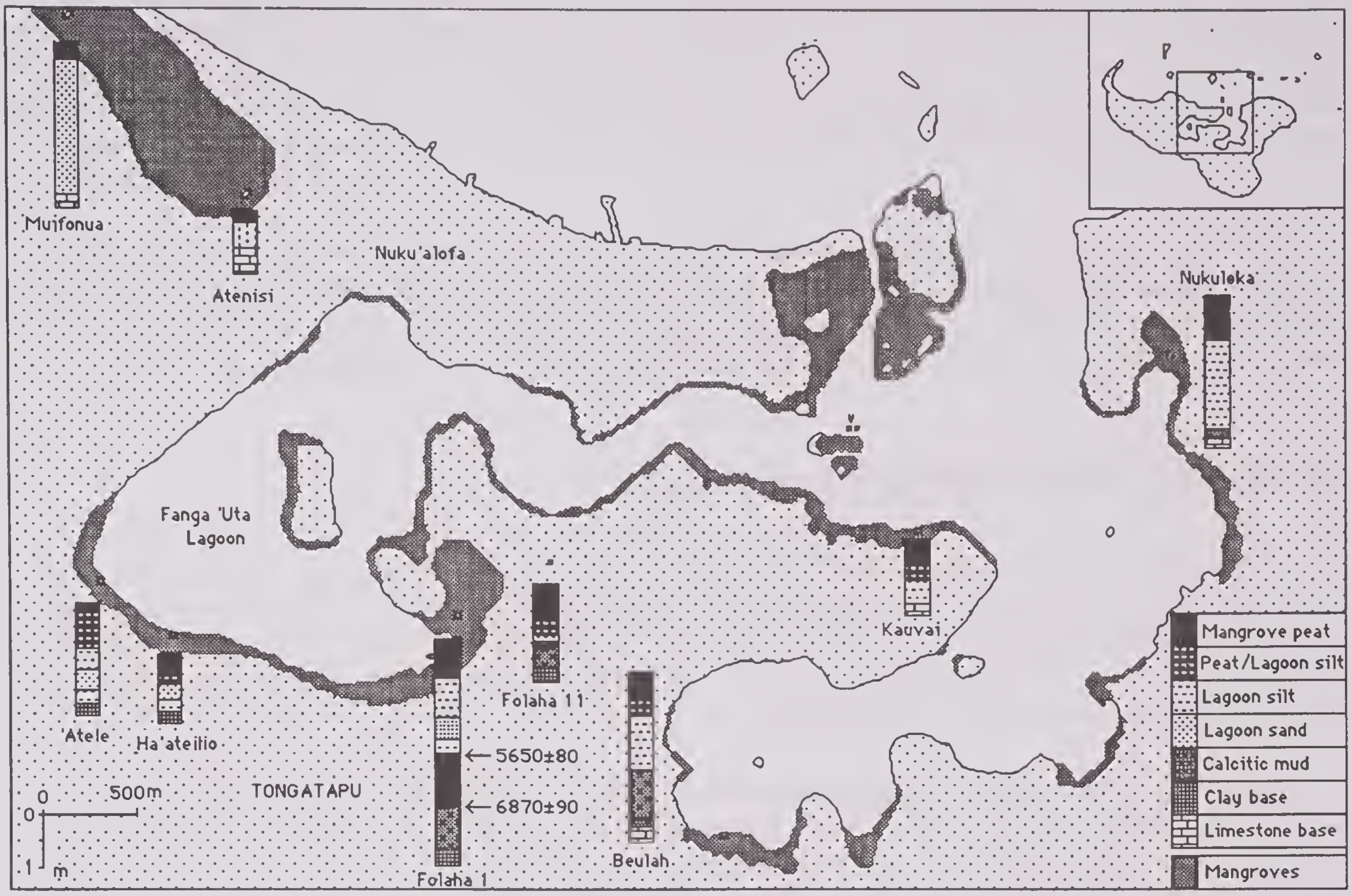
Embayment, harbor, and lagoon mangroves can be extensive where fine sediment accumulates to form a broad intertidal slope. Low-island mangroves do not have an external supply of sediment, and build up their substrate by accumulation of vegetative detritus to form a highly organic peat.

In Tonga, Tongatapu is a low, flat, limestone island, possessing mangrove fringes on its sheltered, leeward northern coast, and around the central Fanga 'Uta lagoon. Stratigraphy of these mangrove areas showed sediment depths of 1-4 meters (Figure 2). At Folaha, the largest mangrove area in the western arm of the Fanga 'Uta lagoon, a mangrove peat occurs at depths of 1.3-2.3 meters below present mean sea level (Ellison, 1989 and 1991). This peat unit underlies all of a 1-km transect across the modern swamp and continues at lower levels beneath the lagoon. The peat in Folaha core 1 formed between 6870±90 and 5650±80 years B.P., giving a rate of peat accumulation in this period of 7.7 cm /100 years. Mangrove assemblages contributing to formation of peat at the levels dated were identified by pollen analysis, and the present elevation of these assemblages has been used to determine past mean sea level. This shows that mean sea level was 3.2 meters below present at 6870±90 years B.P., and 1.7 meters below present mean sea level 5650±80 years B.P. (Ellison, 1989). The rate of sea level rise through the lower peat unit was 12.2 cm/100 years.

During this period of slowly rising sea level, the mangrove ecosystem was able to persist by raising substrate levels at a roughly equivalent rate by peat formation. It was drowned out by more rapid sea level rise, shown stratigraphically by transition from mangrove peat to overlying lagoonal sediment. This is the earliest Holocene peat-building mangrove ecosystem in the Pacific, developing before other locations, owing to the protected location of this part of the lagoon.

Mangrove stratigraphy from low-island mangrove ecosystems indicates rates of accumulation of 8–11 cm/100 years. The rate from Tongatapu is similar to rates of peat accumulation from other low islands—e.g., Grand Cayman (Woodroffe, 1981) and Bermuda (Ellison, in press), shown in Table 2.

FIGURE 2. COASTAL STRATIGRAPHY OF CENTRAL TONGATAPU, TONGA



Core depths indicate low sedimentation rates on this low island.

ANALYSIS

Mangroves on low islands are more susceptible to disruption by rising sea level because the only sediment available is produced by the trees themselves, giving relatively low rates of sediment accumulation. Stratigraphy from high islands and continental coastlines, that have more sediment coming off the land into intertidal areas from rivers and longshore drift, indicates that mangrove ecosystems will be better able to keep pace with sea level rise. Low-island mangroves could keep up with sea level rise of 8 cm/100 years, and have problems with rates over 12 cm/100 years. High-island mangroves could keep up with rates of 20 cm/100 years, provided the sediment supply is not restricted by construction, such as dams on rivers leading to mangrove deltas. These differences are clearly illustrated by Figures 1 and 2, with deep sediment on Kosrae and shallow sediment on Tongatapu over the same time period.

These rates must be compared with those of the IPCC's projections of sea level rise. In the last 100 years, there has been about a 10-cm rise in eustatic sea level. A future eustatic sea level rise of 0.3-0.5 meters is predicted by 2050, and 1 meter by 2100 (IPCC, 1990). This projects mean rates of rise of 50–90 cm/100 years over the period. It is indicated that island mangroves will experience serious problems with rising sea level in the next 50 years, and low-island mangroves could already be under stress.

Stratigraphic records indicate that in the earlier Holocene, when rates of sea level rise were rapid as ice sheets melted, expansive mangrove ecosystems did not exist. Rather, mangroves occurred as disorganized, patchy individuals with dominant flushing of organic material away from their roots, as seen today on more exposed or disturbed shorelines. As sea level stabilized in the mid-Holocene, the first expansive mangrove ecosystems established in sheltered locations. This is shown in stratigraphy by the appearance of mangrove peat, formed from organic accumulations beneath large mangrove ecosystems. Today, after a long period of stable sea level or slow sea level rise, expansive mangrove ecosystems are common in sedimentary shorelines that have developed.

It would seem that in conditions of more rapid sea level rise, mangroves undergo ecosystem collapse, and retreat from their expansive mode into patchy, disorganized refugia. It is clear that low islands are the most vulnerable to loss of mangrove ecosystems during sea level rise, but all mangroves will be severely threatened by the rates of sea level rise projected for the future.

SEA LEVEL TRENDS IN THE PACIFIC REGION

Due to interactions between Late Pleistocene deglaciation and hydro-isostatic adjustment, it has been modelled that the south-central Pacific experienced a stand of sea level higher than present during the mid-Holocene (Clark et al., 1978; Clark and Lingle, 1979). This is modelled to have peaked around 5000 B.P., and declined in magnitude from +1.7 meters at 40°S, through +0.8 meters at 22°S to +0.2 meters at the equator.

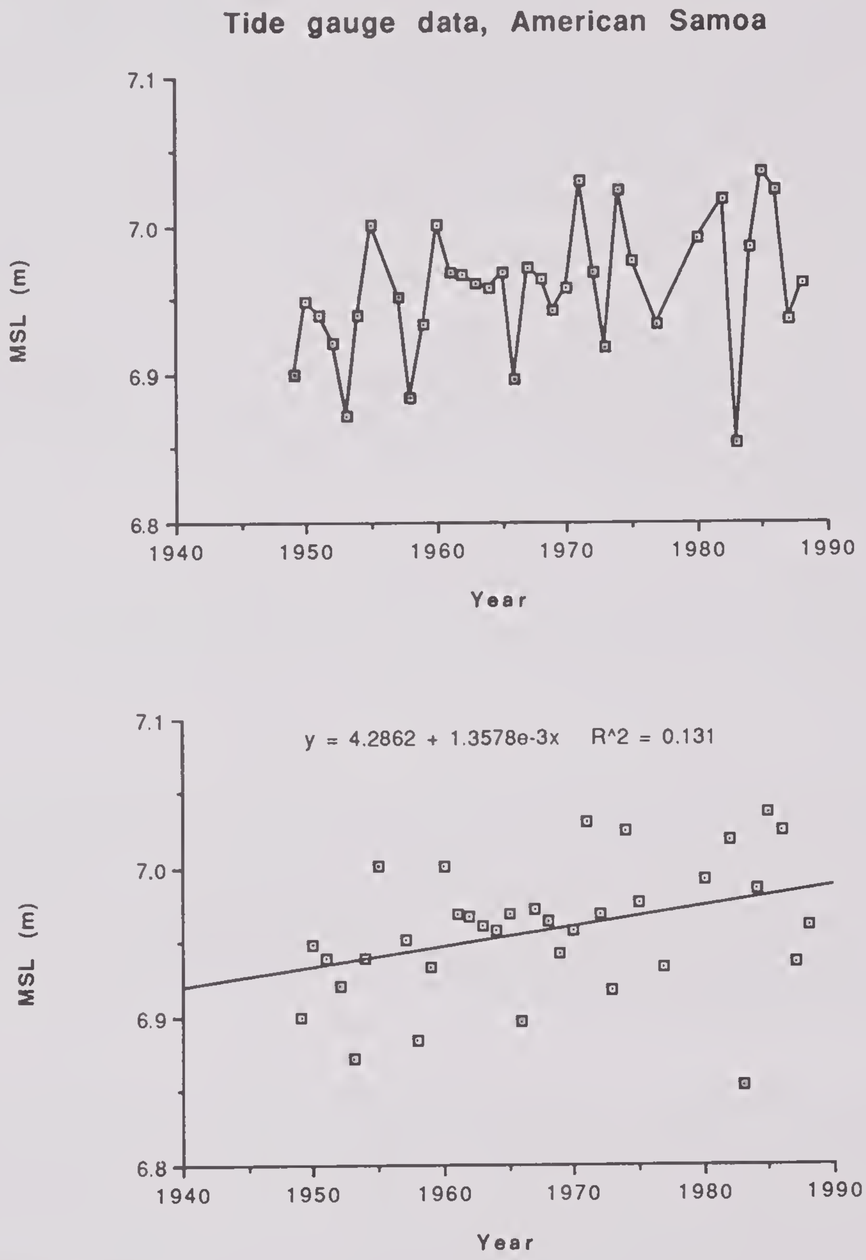
There is a growing consensus of evidence in support of this regional highstand, especially within the latitudes of 10–30°S. In north Queensland, Chappell et al. (1983) show sea level fall from +1.0 meter since 6000 B.P. In New Caledonia, Bourrouilh-Le Jan (1985) shows sea level to be +2.5 meters at 3500 B.P. and Coudray and Delibrias (1972) show sea level to be + 2.1 meters 2200 B.P. In Fiji, Nunn (1990) analyzed sea level records to show that the Holocene transgressive maximum reached 1–2 meters above present mean sea level some 3000 to 2000 B.P. In the Cook Islands in the south, Spencer et al. (1988) show from Mangaia that sea level stood at +1.3 meters 5000 B.P. and +1.7 meters 3.400 B.P., and in the north Scoffin et al. (1985) show from Suwarrow atoll that sea level stood at +0.5 meters 4700 to 2400 B.P. In French Polynesia, Pirazzoli and Montaggioni (1988) analyzed raised reefs and notches to show mean sea level +0.8 to +1.0 between 5000 and 1200 B.P., and a short-lived sea level peak at +1.0 meter was identified between 2000 and 1000 B.P.

This widespread record of a higher sea level in the Pacific islands in the last 6000 years is of significance in consideration of longer-term impacts of sea level rise on coastal systems in the Pacific relative to the Caribbean Sea or the Indian Ocean. On most Pacific islands, relic shorelines 1–2 meters above the present sea level exist, erosional benches or depositional sedimentary levels or fossil reefs, recorded in the research reviewed above. While the levels exist for mangrove establishment at a higher sea level, these are also the land areas favored by human settlement; hence, mangrove migration onto these levels may be restricted.

The highstand record is not synchronous partly because of the heterogeneous tectonic movements of Pacific islands. Like any coastal locations, subsiding areas will have a greater problem with sea level rise than emerging areas. In the Pacific islands, S. Tonga, N.E. Fiji, the Philippines, and Micronesia are shown to be uplifting (Ellison, 1989; Nunn, 1990; Emery and Aubrey, 1991, and Tracey et al., 1964). The south shore of Viti Levu and the southern islands of Fiji are shown to be subsiding (Nunn, 1990), and it is believed that Samoa is also subsiding (Green and Richards, 1975). However, the rates of tectonic change are largely minimal, relative to the rates of sea level rise predicted to occur with climate change.

The longest tidal gauge record from the Pacific islands is from Pago Pago in American Samoa, with records since 1948, (Figure 3) giving a rate of rise of 18 cm/100 years (Emery and Aubrey, 1991). Using two different methods of analysis for 231 tidal guage stations (excluding Fennoscandia), Gornitz and Lebedeff (1987) find a global average sea-level rise of 12 and 10 cm/100 years. The record of sea level rise in Samoa is above average, consistent with the record of subsidence. It is apparent that lower sea level during ENSO events (1983) reduces the rate of rise from the Samoan record.

FIGURE 3. TIDAL GAUGE RECORD FOR PAGO PAGO, AMERICAN SAMOA



MANGROVE PROBLEMS WITH SEA LEVEL RISE

Having identified from the stratigraphic record that mangroves can only keep up with slower rates of sea level rise, it is now necessary to consider the problems that can be expected if sea level rise exceeds the rate of sedimentation.

EROSION

With rising sea level, sediment from the upper part of the tidal range is eroded and deposited subtidally, as shown in modelling of beach erosion (Bruun, 1962; Schwartz, 1967 and 1968).

Mangrove swamps occur from mean tide to high tide, so if sedimentation does not keep pace with rising sea level, then erosion of the substrate can be expected. This should develop before problems are apparent in adjacent beach areas, as the sediment of mangrove swamps is finer than beach material. Three types of erosion can be expected:

- *Cliff erosion of the sediment at the seaward edge.* Loss of the seaward zone leads to truncated zonation, narrower fringes, undercutting of mangrove roots, wind throws. Management responses could be stabilization and protection from further erosion, by use of friction matting placed on the sediment surface, or more natural fibrous material, such as woven palm fronds. Once sediment is built up against the eroding edge is stabilized, it could be replanted with mangrove propagules.

- *Sheet erosion across the swamp surface of leaf litter and peat.* Loss of leaf litter affects the faunal food chain and introduces a positive feedback, as litter cannot accumulate to form peat. The result is migration of pioneer/seaward mangroves into more landward zones. Mangrove management authorities should monitor sedimentation rates within the mangrove ecosystem, by long-term observation of calibrated stakes, and should quantify litter fall (see Brown, 1984). The leaf litter retention of the substrate surface could be enhanced by use of floating oil booms across creeks, as most loss of organic matter from swamps is dry, floating leaves. If leaves are retained by a boom and returned up the creek by the next flood tide, once they are wet they are less buoyant and so are more likely to remain *in situ*. It is not possible to use a barrier to depth, as this would disrupt fish movements.

- *Tidal creek bank erosion.* This causes slumping of banks and loss of trees, owing to more active tidal currents, particularly rapid ebb currents. Management responses should enforce prohibition of boats with motor propellers and jet skis from mangrove areas, as wake waves will enhance the erosion of creek banks.

The understanding and prediction of global sea level trends is only possible through a coordinated system of tidal gauges, such as the UNESCO (Intergovernmental Oceanographic Commission) Global Sea Level Observing System (GLOSS), or the National Oceanic and Atmospheric Administration (NOAA) network. The establishment of such tidal gauges in areas with mangroves should be supported, as this will allow the identification of trends of sea level that may be problematic to mangrove ecosystems.

For identification of problems related to rising sea level, the elevation of the mangrove substrate in different zones should be surveyed with respect to tidal gauge datum. Such surveys will indicate the preferred elevations of different mangrove species, which will be of use should replanting become necessary with sea level rise. Also, they could identify areas low in the tidal spectrum that may already be experiencing problems with erosion. Surveys over time should indicate this better, combined with monitoring of sedimentation rates, by using calibrated stakes. A permanent benchmark should be established close to each mangrove area, to which different surveys can be related for comparison.

INUNDATION STRESS

Impoundment of mangroves for mosquito control provides an analogy for effects of increased inundation. Harrington and Harrington (1982) recorded extensive death of *Avicennia germinans* and *Rhizophora mangle* at India River, E. Florida, following four months of 30-45 cm depth of flooding of an impoundment. Naidoo (1983) found that prolonged flooding resulted in reduced rates of photosynthesis in *Bruguiera gymnorrhiza*, and Lahmann (1988) found that rates of litter fall reduced during flooded months of an impounded *Rhizophora mangle* forest in Florida. When lenticels of aerial roots become inundated, oxygen concentrations in the plant fall dramatically (Scholander, 1955). If inundation is sustained, anoxic conditions and mortalities follow. This is thought to have been the cause of widespread mortality of *Avicennia germinans* stands in Puerto Rico recorded by Jimenez et al. (1985), following permanent flooding as a consequence of adjacent dredging.

It is possible that increased inundation with sea level rise may cause stress in this manner, resulting in reduced net primary production. Mangrove managers can expect the consequences to be reduced growth, reduced litter fall, and reduced production of propagules. Variable tolerances of species to inundation would promote landward migration of species zones by death of older trees and successful seedling establishment in zones of higher elevation than previous. The soil depth of anoxic conditions can be monitored over time, by observation of the oxidized level on an iron stake inserted in the sediment. Changes over time in community composition can be monitored by vegetation surveys.

INCREASED SALINITY

Increase in salinity in mangroves leading to salt stress can result from a number of factors: sea level rise, ground-water depletion owing to reduced hydraulic gradient, ground-water extraction, and reduced rainfall. Two major physiological adaptations enable mangrove survival in saline ocean water (Scholander et al., 1962): salt exclusion in species of *Rhizophora* and *Laguncularia*, and salt excretion in species of *Aegealitis* and *Aegiceras*. Salt excluders not only operate ultrafiltration, but also cease or diminish transpiration and photosynthesis when exposed to saline water. Salt secretors can continue photosynthesis using ocean water in transpiration, owing to salt glands in the leaves.

A number of experiments have shown that increased salinity leads to reduced seedling survival and growth, and decreased photosynthetic capacity (Stern & Voight, 1959; Ball and Farquhar, 1984). Mangrove managers can expect salinity stress of some mangrove species, indicated by reduced growth, reduced litter production, and death. Successful seedling establishment may occur more landward than previously, resulting in retreat of species zones. Limitation of ground-water extraction in the catchment or promotion of sedimentation within the mangroves could mitigate this impact.

Mangrove areas should be mapped and remapped periodically, to show the location of different mangrove zones, and of seaward and landward fringes of the mangrove area. Older records from the mangrove area should be compiled into a data base. Large-scale color air photographs should be taken. Information on the history of sites should be compiled from climate records, previous studies, and records of logging or other activities. This would allow identification of community changes resulting from increased frequency of inundation or salinity.

MONITORING STRATEGIES

Monitoring activities in mangrove ecosystems will greatly assist identification of problems resulting from sea level rise as they start to occur, and will help decisions regarding active management strategies. Certain identification of climate change and sea level rise effects requires long-term monitoring of biological and physical parameters in mangrove swamps at many different locations. This is the intention of the UNEP-IOC-WMO-IUCN long-term global monitoring system of mangroves and coral reefs. At an expert meeting in Monaco in December

1991, key parameters for measurement were selected, and now contacts are being sought for the implementation of the system.*

PARAMETERS

Measurements of biological indicators (listed below) and certain physical parameters should be made along a transect across the intertidal slope, as close to the center of the area as possible. Sampling frequency along this transect will depend on the scale and characteristics of the site. Further to the systematic study specified below, resurvey should be made immediately following an extreme event (cyclones, etc.).

The following biological indicators in Table 3 are the minimum necessary to assess the impact of possible climate change and sea level rise on mangrove ecosystems.

TABLE 3. MINIMUM BIOLOGICAL REQUIREMENTS

Parameter	Minimum Frequency	Methodology
Forest structure	5 years	ASEAN-Australia Manual or USM Manual**
Tree size	5 years	ASEAN-Australia Manual or USM Manual
Density	5 years	ASEAN-Australia Manual or USM Manual
Tree growth	5 years	DBH increment (USM Manual)
Leaf area index	5 years	Light attenuation: ASEAN-Australia Manual with modifications
Interstitial macrofauna	2 years	Holme & McIntyre, 1971; Hulings & Gray, 1971
Species composition of macrofauna	1 year	Burrow density

Because of the diversity of mangrove environments and in order to distinguish between the effects of climate change and anthropogenic and other nonclimate impacts, Table 4 presents the minimum required physical parameters.

TABLE 4. MINIMUM PHYSICAL REQUIREMENTS

Parameter	Minimum Frequency	Methodology
Relative sea level change	Continuous	GLOSS or tide gauge, part of met. station
Topography	5 years	EDM survey, relative to datum
Stratigraphy	Baseline	Coring and radiometric dating
Sedimentation rate	5 years	Inserted stakes, remain *in situ*
Meteorological data	Continuous	Automized meteorological stationto WMO standards
Total radiation		
Air temperature		
Rainfall		
Wind speed and direction		
Relative humidity		
Atmospheric pressure		
Evaporation		Evaporimeter, WMO standards

Further to these minimal requirements, it would be desirable where possible to monitor the indicators in Table 5, to allow assessment and interpretation of biological responses to climate change and sea level rise.

TABLE 5. ADDITIONAL INDICATORS RECOMMENDED FOR MONITORING

Parameter	Minimum Frequency	Methodology
Biological		
Analysis of leaf pigments and tannins	5 years	Tannin analysis of treetop leaves
Height of pneumatophores	5 years	Ruler with EDM survey
Physical		
Sediment particle size	5 years	Sieve cascade, ASEAN-Australia manual
Redox potential	5 years	Inserted iron stakes, removed
Soil salinity	Seasonal	Squeeze cored sediment
Surface water temperature	Seasonal	Maximum/ minimum recorder

For a more complete analysis, the parameters in Table 6 could also be examined, which could assist in interpretation of the biological responses.

TABLE 6. DESIRABLE INDICATORS FOR MONITORING

Parameter	Minimum Frequency	Methodology
Biological		
Age distribution of macrofuana	5 years	ASEAN-Australia Manual
Predawn water potential	5 years	Scholander pressure bomb
Physical		
Wave conditions		Derive from meteorological data
Water circulation		GCNSMS Activity 2
Sediment ash free dry weight	5 years	Loss on ignition
Trace metals	5 years	To international standards
Pesticides	5 years	To international standards
Root flora	1 years	Qualitative observation
Carbon partitioning	5 years	To be determined
Rate of turnover of biomass	5 years	To be determined
Litter breakdown	5 years	To be determined

This long-term monitoring will identify response of mangroves to climate change and sea level rise, with elimination of concurrent response to some other forcing factor by site comparison.

CONCLUSION

Sea level position is central to the functional ecology of a mangrove swamp. Rise in sea level will perturb every aspect of the ecosystem, and combined with the effects of climate change, stresses from storms, and human disturbances, the world's mangroves are likely to face severe disruption in the next few decades. Effective understanding and management of the problems require an applied direction among the different mangrove scientists and communication among them and with those responsible for the conservation and sustainable use of mangrove forests. The effects of climate change and rise in sea level will also vary among mangroves in different parts of the world and in different physiographic locations, due to such factors as productivity, species composition, and sediment supply. Here also, communication among the management personnel of different countries will allow separation and analysis of problems of local and regional scales.

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* Government departments or research institutes interested in taking responsibility for long-term monitoring of a mangrove or coral site should contact Ms. Muriel Cole, Senior Assistant Technical Secretary, Intergovernmental Oceanographic Commission, UNESCO, 7 Place de Fontenoy, 75700 Paris, France. Fax: +1 40.56.93.16

** The ASEAN-Australian Manual of Survey Methods for Living Resources in Coastal Areas is being revised for the UNEP-IOC-WMO-IUCN long-term global monitoring system of mangroves and coral reefs, to be released in mid- 1992. This is being coordinated by Barry Clough (mangroves) and Clive Wilkinson (coral reefs) at the Australian Institute of Marine Science.

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PROBABILITY DISTRIBUTION OF FUTURE SEA LEVEL RISE

James G. Titus
Climate Change Division
U.S. Environmental Protection Agency
Washington, D.C.

Vijay Narayanan
The Bruce Company
Washington, D.C.

INTRODUCTION

In the last several years, a steady stream of reports have estimated that the rate of sea level rise is likely to accelerate in the next century (EPA, 1983; NRC, 1983 and 1985; IPCC, 1990). As a result, coastal decision makers around the world have gradually begun to consider how to respond. In most cases, no immediate response is necessary because the time required to implement a response is less than the time likely to pass before the sea rises significantly (NRC, 1987).

While the consensus has strengthened that an acceleration is likely, the more recent studies have estimated that the magnitude of the rise will probably not be as great as projected by a few of the earlier reports. This downward revision has resulted largely from a corresponding reduction in the estimates of future concentrations of greenhouse gases: While the earlier studies projected a 4°C warming by the year 2050, the recent studies assume that such a change in climate is unlikely before 2100.

Differences in the methods of these studies have also led to the downward revision of the estimates. In 1983, EPA published the first report on the subject (Hoffman et al., 1983), which presented several dozen scenarios with estimates of thermal expansion ranging from 8 to 115 cm by 2100. Based on historic relationships, the report assumed that the total contribution would be two to three times thermal expansion. Later that year, Roger Revelle estimated that the thermal expansion contribution was likely to be 30 cm by 2080. Using "back-of-the-envelope" procedures, he also estimated that the total rise in sea level would be about 70 cm.

The first serious attempt to estimate the possible glacial contribution to sea level change arose from a symposium sponsored by the U.S. Department of Energy, which produced over two dozen papers. A special panel of the National Academy of Sciences' Polar Research Board (PRB, 1985) reviewed and integrated the symposium's results. A paper by Mark Meier, the panel chairman, suggested that mountain glaciers could increase sea level rise by 10 to 30 cm by 2100; a two-dimensional model by NASA's Robert Bindschadler showed that a similar magnitude could be expected from Greenland. Several papers addressed different mechanisms by which Antarctica could affect sea level. These included increased precipitation, warm intrusions of water beneath ice shelves, increased ice shelf melting, and ice stream response to shelf thinning. Integrating the various mechanisms and the various results, the PRB concluded that the Antarctic contribution could be between -10 cm and +100 cm through 2100.

The Intergovernmental Panel on Climate Change (IPCC, 1990) used a one-dimensional upwelling-diffusion model to estimate that the thermal expansion contribution would be 25 to 60 cm, broadly consistent with the previous reports. Its estimates of the alpine (8 to 22 cm) and Greenland (3 to 28 cm) contributions, while a bit lower, were also consistent with the PRB estimates. The procedures for Antarctica, however, departed markedly from that of the PRB: rather than estimating potential ice shelf thinning and the resulting acceleration of ice streams, IPCC assumed that those processes would have no contribution through the year 2100, even in the high scenario. Because IPCC did consider the potential for increased Antarctic precipitation, it estimated that the Antarctic contribution would be between -7.6 cm and zero.

Unfortunately, previous publications have not ascribed probabilities to their projections, for both computational and conceptual reasons. At the computational level, projections of sea level rise require complex nonlinear functions. Hence, even if we knew the distributions of the various unknowns, probability theory would offer us no direct "closed-form" solution for estimating the probability distribution of future sea level rise. Instead, one must iteratively approximate the distribution by evaluating the models with alternate values for the various unknowns. But many models—particularly general circulation models—cost too much to run for this to be possible.

Even where the computational problems can be solved, estimation of probability distributions involves an additional degree of apparent subjectivity. Measurements of various processes may lead researchers to be confident that a particular set of low, medium, and high scenarios is reasonable. But ascribing probabilities requires an additional level of specification, and current knowledge does not permit this to be done with precision. For example, both Meier (1990) and IPCC (1990) report the results of committees that agreed to a high scenario in which the Antarctic contribution to sea level rise is zero. The committees did not, however, decide whether the high estimate represents a worst-case scenario, or a "one σ" limit with some chance of being substantially exceeded. Moreover, if they had decided upon the latter interpretation, it would have been even more difficult to estimate the probability of the exceedence, or the rise associated with its occurrence.

Despite the difficulties of estimating probability distributions, there are many reasons to do so:

- First, decision makers need this information. A number of important decisions are sensitive to sea level rise on time scales of a century or so. In some cases, the cost of preparing for too little sea level rise is so much greater than the cost of preparing for too much sea level rise that it is rational to design for a relatively high (and unlikely) scenario. For example, the Dutch flood-protection system is designed to endure the "ten thousand year storm," which has only a 1 percent chance of occurring in a given century (Goemans, 1986). Thus, if a new project is expected to last a century, maintaining the desired level of safety requires an explicit consideration of the probability distribution of sea level rise. Similarly, if a state intends to protect its coastal wetlands, the cost of anticipatory land use planning can be less than 1 percent of the eventual cost of remedial action (Titus, 1991); thus it can be rational to implement environmental policies for any area whose probability of inundation by the year 2100 exceeds 1 percent (Titus, 1991).

- Second, if the published literature does not provide information on probabilities, decision makers and analysts must implicitly or explicitly make their own assumptions, which are likely to be less accurate than the results of expert panels.

- Finally, focusing on probability distributions may foster scientific cohesion by enabling scientific panels to avoid choosing sides in matters of scientific uncertainty, and instead simultaneously lend partial credence to competing, contradictory viewpoints, until one or the other is disproved.

This paper presents the first phase of an effort to estimate the probability distribution of future sea level rise implied by the expectations of current climate researchers. In this first phase, we describe a simplified model for estimating sea level rise as a function of 35 major uncertainties, and the results of a Monte Carlo experiment using 10,000 simulations with distributions of each of the uncertainties derived from the existing literature. The following sections discuss our methods, our assumptions regarding concentrations of greenhouse gases, global temperature change, ocean thermal expansion, Greenland, Antarctic and Alpine contributions to sea level, and a summary of our results. The results presented herein represent the probability distribution derived from the authors' interpretation of the literature. An important aspect of this study is that we avoid the use of "low" and "high" scenarios in favor of explicitly calculating the probability distribution of future sea level. In so doing, we are responding to the recommendation of an NRC panel of coastal scientists and engineers, which concluded that "[p]ractitioners can more readily incorporate the implications of sea level rise if probabilities reflecting uncertainties are attached to the projections," and recommended that "all updated projections include such information." (NRC, 1987).

In the second phase, we plan to assemble delphic panels to specify the distributions of each of the major uncertainties. The resulting "delphic Monte Carlo analysis" will provide the probability distribution implied by the expectations of the climate experts of today. A more detailed description of our methods and results for both phases will be published in EPA (1994).

ANALYTICAL METHODS

Our overall approach is to assume that:
SL = M(a,b,c,...),
where SL is sea level,
M is the model, and
a, b, c,... are unknown coefficients.

We assume that the model would be true if we know the actual values of the coefficients. But because no one knows their precise values, we must rely on estimates, each of which are uncertain. Based on available estimates, and reasonable assumptions about the shapes of the distributions, one can estimate a probability density function for each coefficient.

In the simple case, where SL = aX + bY and we have data on X and Y, probability theory provides us with a simple formula for estimating the distribution of SL. However, projections of sea level rise are nonlinear. Even simple models must multiply uncertain temperatures by uncertain melting-sensitivity parameters, and most models are far more complex. Under these circumstances, solving for the distribution is too complicated to be practical.

Nevertheless, statisticians have shown that one can eventually converge on the distribution by randomly selecting values of the coefficients, running the model repeatedly, and treating the resulting estimates as a sample. This procedure is known as "Monte Carlo." Because we wanted to estimate the rise with a 1 percent chance of being exceeded, 10,000 trials seemed to be sufficient.

Table 1 lists 35 parameters for which we characterize probability distributions that we derived from the literature. However, in four cases we used alternative models for which we specified n-nomial distributions based on our best guess about the combined opinion of the community. For example, if we have two alternative models for estimating thermal expansion of ocean water, we assume that there is a chance of p that $SL = M_1(a,b,...)$ and a chance of (1-p) that $SL = M_2(a,b,...)$. Although this approach allows us to relax the assumption that a particular model is true, it still understates our uncertainty, because there is a chance that none of the models that we specify is either a true or a reasonably accurate summary of the likely response of the relevant processes.

Like most previous assessments of sea level rise, we focus on the year 2100. However, we do not truncate our analysis at that date because:

- Some glacial modeling efforts have suggested that impacts from Antarctica will not be significant until after that point (e.g. Huybrechts and Oerlemans 1990; Thomas, 1985).
- Decision makers can decide for themselves which years to employ; hence it is better to err on the side of providing too long of a time horizon.
- Longer time horizons provide a better understanding of the implications of one's assumptions.
- The impacts likely to occur over longer periods of time are similar to the worst-case scenarios of what could happen in the next century.
- Cline (1992) makes a compelling case for extending all climate impact analyses out for at least 200 years.

This analysis attempts to take advantage of the superior features of the PRB and IPCC studies and to avoid their weaknesses. Where possible, we have used IPCC assumptions, and we use the IPCC models for estimating future concentrations, global temperatures, thermal expansion, and alpine contribution; and our Greenland model yields results similar to the IPCC model. However, because the IPCC assumption of no Antarctic contribution does not reflect the consensus of glaciologists, we have used a variety of models, including the IPCC assumption, the PRB assumptions, and linearization of the results from the IPCC's lead author on sea level rise. The resulting calculations suggest that the contribution from Antarctica probably will be negligible, as IPCC concluded, but that there is a 10 percent chance of a positive contribution and a 1 percent chance that the contribution will exceed 10 cm by the year 2100 and 100 cm by the year 2200.

Following is a brief description of how we calculated concentrations of greenhouse gases, global temperatures, and thermal expansion, and the contributions of alpine, Greenland, and Antarctic glaciers.

CONCENTRATIONS OF GREENHOUSE GASES

Our assumptions for concentrations required us to project emissions and then to use a model of atmospheric fate to estimate concentrations. For all gases other than CFC-11 and CFC-12, we calculated the geometric means and standard deviations of the six IPCC scenarios through the year 2100, and characterized the shape of the distribution based on a previous Monte Carlo analysis from the 1983 NAS report *Changing Climate.* Because some of the IPCC scenarios for CFC-11 and CFC-12 show the gases declining to zero, the geometric standard deviation is undefined; hence we simply assumed the six IPCC scenarios to be equally probable.

In all cases, we used the same models as IPCC to relate emissions to concentrations. Like the IPCC, we did not consider a range of atmospheric lifetimes for each gas; therefore, we may be understating our uncertainty somewhat. We assume that emissions are constant after the year 2100, but that concentrations gradually approach an equilibrium level.

As a result of these assumptions, our median estimate of atmospheric forcing of 6.2W/m^2 for 2100 is very close to that of the IPCC's IS92a. Our calculated 90 percent confidence interval is 3.75 to 10W/m^2.

GLOBAL TEMPERATURES AND THERMAL EXPANSION

Like the IPCC (1990), we use the Wigley and Raper one-dimensional upwelling-diffusion model to relate greenhouse gas concentration changes to global temperatures, and thermal expansion of ocean water. Unlike that and other previous efforts, however, our scenarios explicitly consider uncertainties regarding the value of π (the ratio of the warming of newly formed bottom water to the warming of surface water) and the sensitivity of vertical advection to global temperatures.

We had several reasons for considering alternate values:

- First, while the IPCC (1990) assumed that $\pi=1$, a number of authors have suggested that a value as low as 0.2 may be more appropriate.

- Second, as long as the upwelling speed is fixed, long-term sea level rise is sensitive to π. If $\pi=1$, we are allowing the entire ocean to warm, expand, and contribute to sea level rise; whereas if $\pi=0$, we are assuming that the warming is mostly confined to the upper layers. For example, if $\pi=1$, thermal expansion is 40 percent greater after 100 years and 90 percent greater after 200 years than if $\pi=0$.

- Finally, coupled ocean-atmosphere models suggest that vertical circulation could weaken as temperatures increase. Other researchers have estimated a decline in sea ice formation, which is responsible for the majority of global bottom-water formation. If the upwelling velocity is allowed to decline, the middle layers of the ocean can warm considerably more than if upwelling is fixed, even assuming a low value of π. For example, even without global warming, a 50 percent decline in downwelling would raise sea level 15 cm in 100 years, according to the IPCC's 1-D model.

In one-half of our simulations, we assume that π is fixed at 0.2 but that upwelling velocity declines. Based on our interpretation of GFDL results, as well as sea ice modeling by NASA, we assume that upwelling declines between 5 and 20 percent per °C warming, with a median of 10 percent. In the other half of the runs, we follow the more conventional approach of keeping upwelling velocity fixed; we assume that π is uniformly distributed between 0.2 and 1.0. In all simulations, we assume that the equilibrium warming is lognormally distributed with σ limits of 1.5 and 4.5°C.

Based on these assumptions and the concentration estimates already discussed, 90 percent of our simulations show a warming of between 1.2 and 6.5°C by the year 2100. Although our median estimate is only 10 percent higher than the IS92a estimate of 2.8°C, our high estimate is closer to the IPCC's high estimate (1990) under the "business-as-usual scenario" than to the IS92 high estimate of 4.2°C.

The higher temperatures at the high end of the range result largely from the lower values of π that are used in some runs, which imply a greater initial response of surface temperatures to greenhouse forcing. Although the lower value of π can have ambiguous effects on thermal expansion, our median estimate is 30 cm by the year 2100, 25 percent less than the IPCC's 1990 estimate. While only 5 percent of our simulations exceed the IPCC (1990) high estimate of 58 cm, 35 percent of our simulations fall below the IPCC low estimate of 26 cm. For the year 2200, our 90 percent confidence interval is 23 to 137 cm.

GREENLAND CONTRIBUTION

Estimating the contribution of Greenland requires us to estimate changes in regional temperature and precipitation, and how the ice sheet would respond to such changes. The IPCC (1990) combined all of these processes into a single equation that assumed the annual contribution to be proportional to the global warming by a particular year. This analysis, by contrast, disaggregates these processes (1) because the NAS analysis suggests that the linear assumption significantly understates the extent of our uncertainty under high-warming scenarios, and (2) because of the desirability of explicitly imposing a mass constraint based on the volume of the ice sheet.

The IPCC (1990) assumed that Greenland would warm 1.5 times the global average; we assume a lognormal distribution with 2σ limits of 1 and 2. Following previous work by Huybrechts and Oerlemans (1990), we calculate the precipitation implied by assuming that precipitation increases as a function of saturation vapor pressure, using alternative functional specifications as our 2σ limits. Finally, we employ the model Bindschadler (1985) contributed to the NAS report to relate climate change to sea level contribution, adapting the model to explicitly recognize the mass of the ice sheet.

With these assumptions, our 90 percent confidence interval for Greenland is 2.2 to 21 cm by 2100, somewhat lower than the IPCC(1990) estimate of 3 to 28 cm. Note, however, that in reviewing how we imposed the mass constraint, Bindschadler has suggested an alternative specification that would result in our projections being about 30 percent greater for the year 2100. For the year 2200, our 90 percent confidence interval is 7 to 100 cm.

ANTARCTICA

Our overall objective in modeling the Antarctic contribution was to adequately reflect both the view of the IPCC and most European glaciologists that Antarctica will not contribute to sea level during the next century, as well as the view of most U.S. glaciologists that Antarctica probably will not contribute significantly, but that a large contribution cannot be ruled out. Our primary obstacle was that although previous *research* papers have analyzed the various processes, previous *assessments* have not explicitly modeled these processes, let alone develop simplified schemes that could be used in a Monte Carlo exercise involving 10,000 simulations.

We began by asking all of the known Antarctic ice sheet modelers for their models if they would be appropriate. Only two indicated that their models could be adapted for our purposes. Robert Thomas supplied us with his ice stream model, which had formed the basis of the PRB's estimate that the Antarctic contribution by 2100 could be as great as 1 meter. Johannes Oerlemans sent us a paper summarizing the results of his model for a hypothetical 1 meter per year thinning of the Ross Ice Shelf; we developed a simple equation to interpolate his results.

Both of these models require us to first estimate the rate at which the floating Antarctic ice shelves might melt, which in turn would be a function of the Antarctic circumpolar deep-water temperature. Because previous assessments did not provide this linkage explicitly, we had to do so based on the literature. The GFDL coupled ocean/atmosphere model suggests that the circumpolar ocean will warm much more slowly than global temperatures. The best fit for a simple first-order linear differential equation suggests that in equilibrium the circumpolar ocean warms only 3/4 as much as the global average, and that the circumpolar temperature lags 40 years behind global temperatures, which already lag atmospheric forcing. Using this as our median scenario, the circumpolar ocean warms by only 1.5°C for a 3.1°C global warming by 2100.

The PRB report provided the basis for estimating shelf-melting rates. In that report, both Stan Jacobs and the full committee discussed the possibility of warmer circumpolar ocean water intruding beneath the shelves, leading to more rapid melting. Based on the existing differences between the temperature of the circumpolar ocean and these colder "warm intrusions," as well as the current rates of net shelf melting, we developed simple linear equations relating circumpolar ocean temperature to shelf-melting rates. Under our median scenario, the shelf-melt rates increase by about 0.3 meter per year by 2100. Following the PRB, we also include the possibility of a sudden switch in which undiluted circumpolar water intrudes beneath the shelves, which could increase the shelf-melt rate by about 2 meters per year, assuming that other parameters take on their median values.

Both Thomas and Oerlemans originally tested their models on scenarios in which the ice shelf-melt rates accelerate by 1 meter per year, which is equivalent to about 22 cm per century of sea level rise. The Oerlemans results suggest that sea level would only rise 2–3 cm per century, implying that only a small fraction of the shelf ice melted would be replaced by new ice flowing into the oceans. By contrast, the Thomas model calculates a 2–3 cm per century rise from the ice conveyed by Ice Stream B alone—which currently only accounts for only 2 percent of the ice discharged by Antarctica. Scaling up Thomas' Ice Stream B results yields estimates that range from 20 to 100 cm per century, implying that iceberg calving might increase as well. Because the scaling is somewhat arbitrary, we also included a disaggregated model in which the several ice streams feeding the Ross and Ronne-Filchner ice shelves are each treated separately, using the Thomas scheme.

Our simulations draw from seven alternative Antarctic models, including the IPCC assumption of no ice stream contribution, the Oerlemans scheme, four different permutations of the Thomas model, and a simple "shelf melt only" model. We also include the negative contribution from increased precipitation. Because most scenarios have shelf-melt rates far below 1 meter per year, the ice stream contribution resulting from even the Thomas model is negligible under most scenarios. Because we include the negative contribution from increased precipitation, the median scenario, for example, is a slight decline. Ninety percent of our simulations have an Antarctic contribution of less than 3 cm by the year 2100; 1 percent of the simulations, however, had a contribution of greater than 16 cm. The models suggest that the substantial impacts once feared are unlikely to happen before the 22nd century, if at all. Our simulations for the year 2200 show a median of about 3 cm, with 10 percent of the simulations exceeding 25 cm and 1 percent exceeding 1.6 meters.

ALPINE CONTRIBUTION

We simply adopted the functional specification of IPCC(1990). In EPA (1994) we identify a number of limitations in this model that are well known to the authors of the IPCC reports; because they are developing an improved model we did not attempt to duplicate that effort.

RESULTS

Figures 1 and 2 show probability distributions for total sea level rise for the years 1990-2030 and 1990-2100 respectively. Figures 3 and 4 show spaghetti diagrams for the Antarctic contribution to sea level rise and the total sea level rise respectively. The spaghetti diagrams show selected runs for years 1990 to 2400 from the Monte Carlo experiment. Runs 1, 2, 5, 10, 20, 50, 100, 200, 400, 600, ..., 9800, 9900, 9951, 9981, 9991, 9996, 9999, 10000 are shown; these indices represent the run number after they have been ranked according to the amount of sea level rise by the year 2200. A subset of these indices has been labeled.

FIGURE 1. PROBABILITY DISTRIBUTION OF SEA LEVEL RISE: 1990-2030

1a

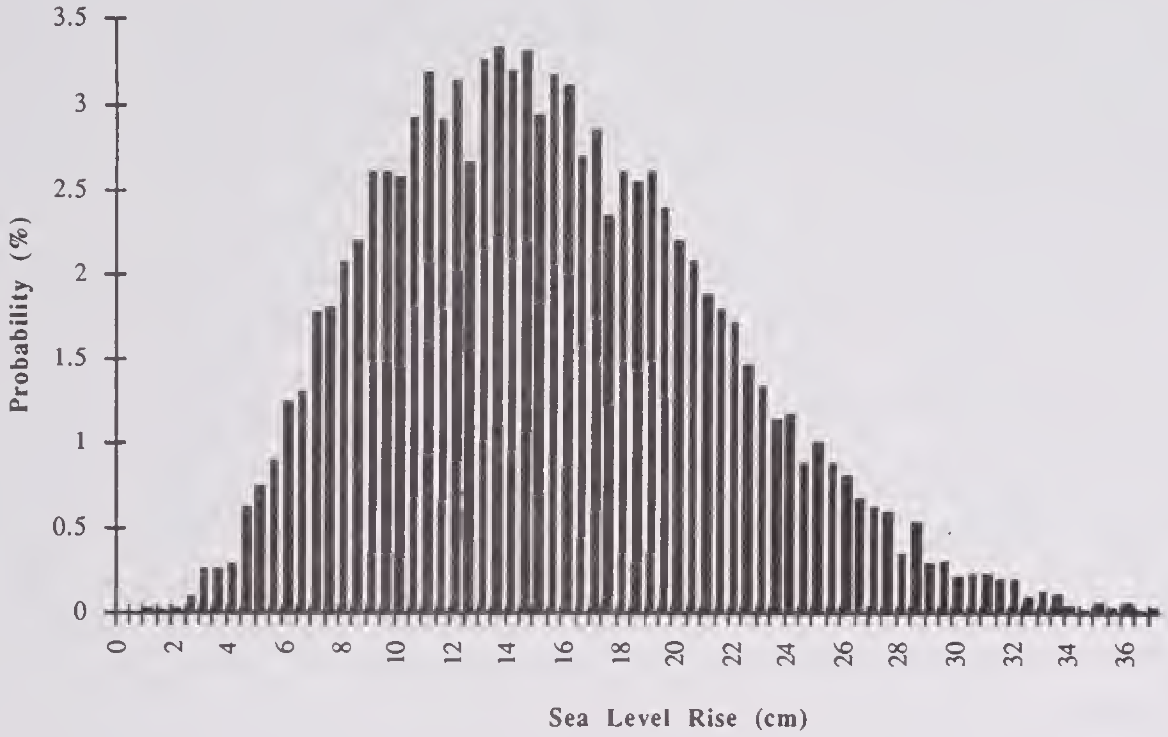


FIGURE 2. PROBABILITY DISTRIBUTION OF SEA LEVEL RISE: 1990-2100

1b

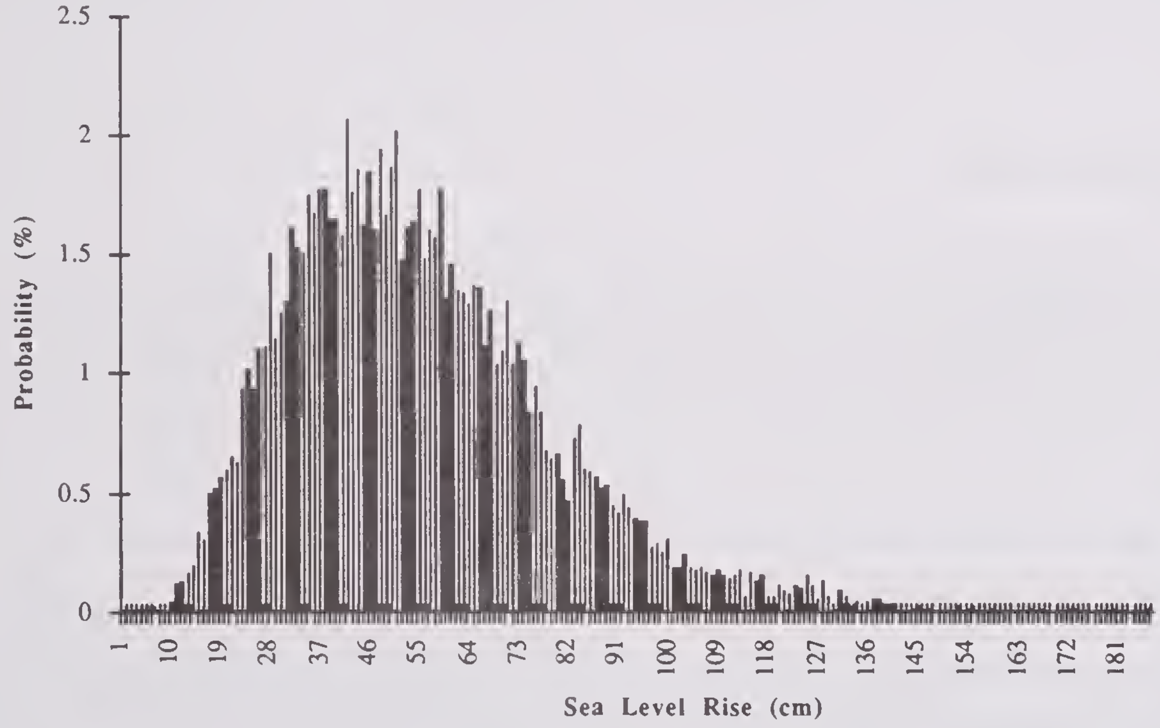
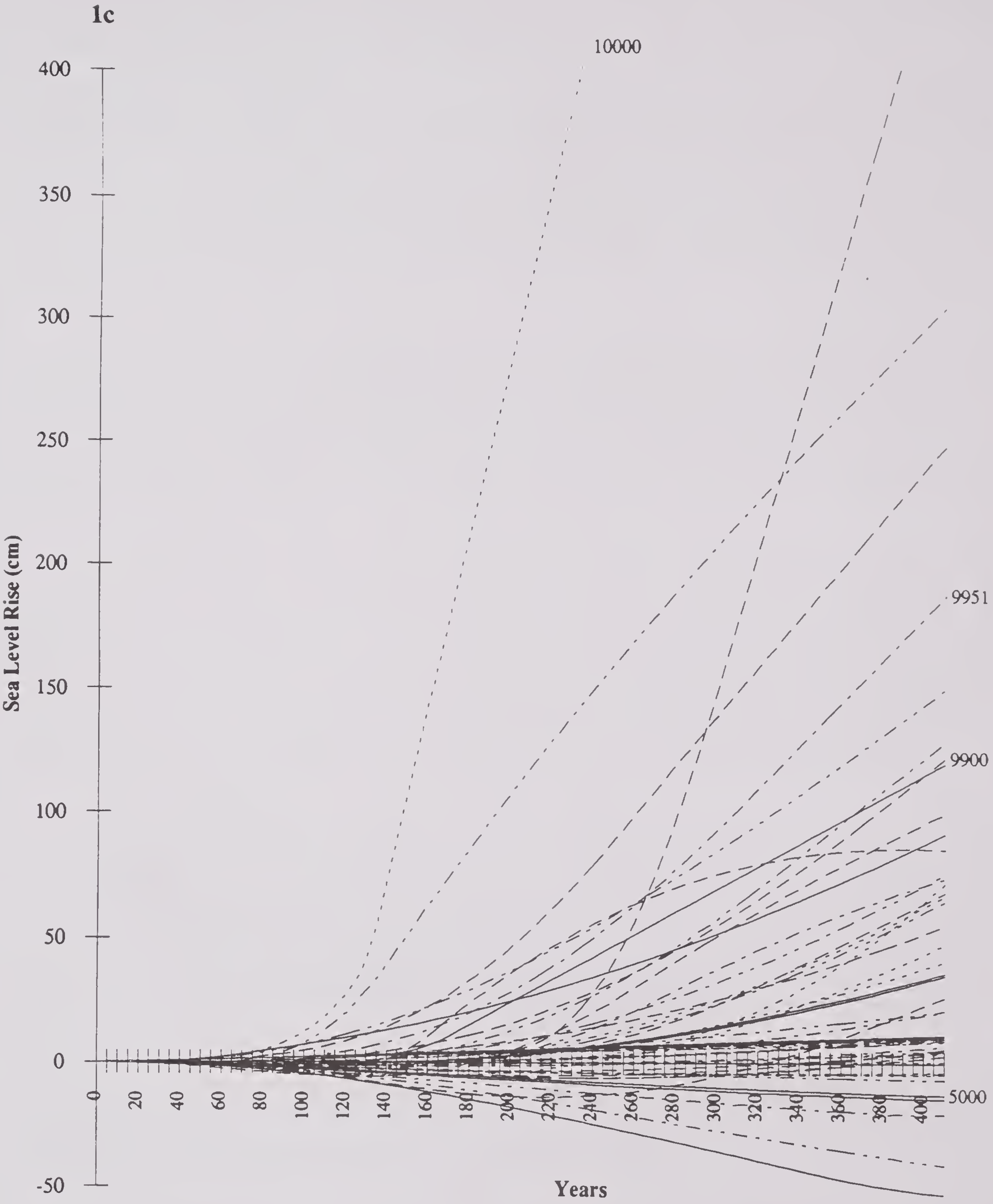
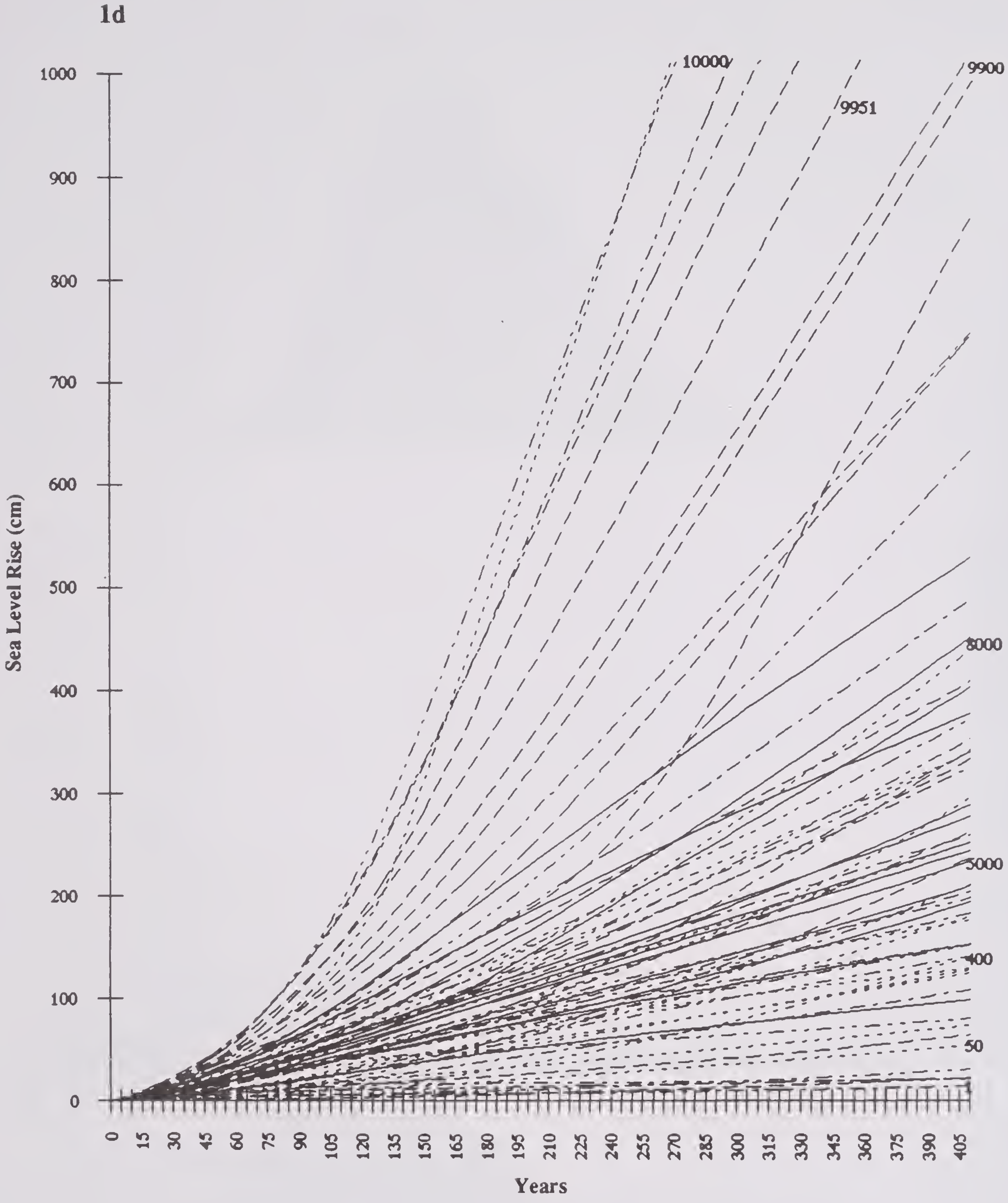


FIGURE 3. SPAGHETTI DIAGRAMS FOR THE ANTARCTIC CONTRIBUTION TO SEA LEVEL RISE



Selected runs for years 1990 to 2400 from the Monte Carlo experiment are shown. Runs 1, 2, 5, 10, 20, 50, 100, 200, 400, 600, ..., 9800, 9900, 9951, 9996, 9999, 10000 are shown; these indices represent the run number after they have been ranked according to the amount of sea level rise by the year 2200. A subset of these indices has been labeled.

FIGURE 4. SPAGHETTI DIAGRAM FOR TOTAL SEA LEVEL RISE



Selected runs for years 1990 to 2400 from the Monte Carlo experiment are shown. Runs 1, 2, 5, 10, 20, 50, 100, 200, 400, 600, ..., 9800, 9900, 9951, 9996, 9999, 10000 are shown; these indices represent the run number after they have been ranked according to the amount of sea level rise by the year 2200. A subset of these indices has been labeled.

Table 2 illustrates the probability distribution of total sea level rise for selected years; Table 3 compares the contributions of various factors; and Table 4 compares our projections with those of IPCC(1990) for the four major components of future sea level rise. EPA (1994) gives a more complete description of the results of both phase 1 and phase 2 of our study.

Overall, our median estimate is 51.5 cm—substantially lower than the IPCC's "best-guess" estimate of 64 cm, but fairly consistent with the Wigley and Raper (1992) estimate of 48 cm. Our 90 percent confidence interval is 22 to 101 cm. Because both the Greenland and Antarctic simulations provide highly skewed distributions, 1 percent of the simulations exceed 1.3 m. Our downward revision of the IPCC estimate is about half due to the lower values of π in the thermal expansion model, a trait shared (to an even greater extent) by the Wigley and Raper analysis. The IPCC's (1992) slight downward revision of future concentration estimates also results in a lower estimate.

The other half of our downward revision is split evenly between mountain glaciers and Greenland. The lower mountain glacier estimates result entirely from incorporating the recent work of Oerlemans and Fortuin (1992) and its suggestion that these glaciers are less sensitive than previously assumed by Meier (1984). The lower Greenland estimates result primarily from our addition of a mass constraint to Bindschadler's model. Slightly offsetting these downward revisions is the upward impact of our median estimate that Antarctica would contribute a sea level drop of only 2 cm, rather than the 5 cm drop estimated by the IPCC.

Examining the entire range of the distribution, it is difficult to say whether our calculations constitute a downward revision, because the term "low" or "high" scenario has no precise meaning. For example, the IPCC's (1990) high scenario involved a coincidence of high temperature sensitivity and high values for the sensitivity of Antarctic, Greenland, and mountain glaciers; but it was based on a best-guess estimate of future concentrations and ocean mixing (although those assumptions are both at the high end of the range we use here). Our results, by contrast, do not explicitly include a coincidence of all parameters reaching their "high values." both because we randomly select the parameter values and because the normal and lognormal distributions that dominate do not have fixed upper bounds.

Nevertheless, given the interpretation of "high" and "low" as "worst case" and "best case," our results appear to reflect far more uncertainty than the IPCC's results. Over 10 percent of our simulations result in less sea level rise than the IPCC's low scenario of 30 cm by 2100, and 1 percent of the simulations would even suggest that the next century will have less sea level rise than the last century's 15 cm. At the upper end of the range, about 4 percent of our simulations suggest more sea level rise than the IPCC's 110-cm high scenario. Thus, while the IPCC's high scenario was 3.7 times its low scenario, our 1 percent high scenario is 8.7 times our 1 percent low scenario, for the year 2100.

Uncertainty increases over time. For example, the ratio of our 1 percent-high to our 1 percent-low scenario is 7.5 for 2030, 8.7 for 2100, and 14 for 2200. This increase would be even greater were it not for the apparent decline in uncertainty for mountain glaciers, which may change when ongoing revisions of the Raper et al. model are completed.

We believe that this analysis is an improvement over previous efforts because it explicitly recognizes many of the uncertainties that those efforts have been forced to overlook. Moreover, we believe that it is more consistent with the consensus of glaciologists than previous efforts, which either overstated the likely glacial contribution (e.g., EPA, 1983) or understated the possible-albeit-unlikely contribution (e.g., IPCC, 1990). These calculations, however, are based on parameter distributions that we selected from the literature primarily with the purpose of testing our methods; as such, they have no significance for planning or policy purposes.

TABLE 1. ASSUMPTIONS OF THIS STUDY

Parameter	**Parameter Distribution** *Name*	*Shape, Moments*	**Value of Moments**	**Correlation with Other Parameters**
CONCENTRATIONS OF GREENHOUSE GASES				
Emissions	E	Nordhaus Yohe, scaled	IPCC92 scenarios	perfect correlation among gases
OCEAN MODEL				
Equilibrium ΔT $2xCO_2$	T_{eq2}	lognormal σ limits	1.5, 4.5 °C	none
Diffusivity	k	lognormal 2σ limits	1000, 3000 m^2/yr	w (1.0)
Probability of Case A	C1	binomial	Prob(C1=1)=0.5	none
Case A: Fixed Bottomwater Formation				
Downwelling Ratio	π	lognormal 2σ limits	0.2, 1.0	none
Upwelling Velocity	w	lognormal 2σ limits	2.0, 6.0 m/yr	k (1.0)
Case B: Bottomwater Formation Declines with Temperature				
Downwelling Ratio	π	Fixed	0.2	none
Upwelling Velocity				
Initial	w_o	lognormal	2.0, 6.0 m/yr	k (1.0)
Transient	w	Declines $e_{w/T}$ per °C	global warming	
Sensitivity of w to Temperature	$e_{w/T}$	lognormal, 2σ	0.05, 0.2	
Equilibrium Polar Amplification				
Antarctic Summer	P1	lognormal, σ	0.67, 1.5	P2 (0.5), P3
Antarctic Winter	P2	lognormal, σ	1.0, 3.0	P1 (0.5)
Greenland Annual	P7	lognormal, 2σ	1.0, 2.0	P1, P2 (0.5)
Circumpolar Ocean	P3	lognormal, σ	0.25, 1.0	P1 (0.75)
Adjustment Times (in addition to the global lag)				
Circumpolar Ocean	P4	lognormal, 2σ	20, 80 years	P5, P6 (0.5)
Antarctic Summer	P5	lognormal, σ	1, 20	P6, P4 (0.5)
Antarctic Winter	P6	lognormal, σ	1, 20	P4 (0.5)
Greenland		Fixed	No Additional Lag	

Parameter	Parameter Distribution		Value of Moments	Correlation with Other Parameters
	Name	*Shape, Moments*		
Polar Precipitation				
Antarctic (approx 6%/°C)	P7	lognormal, 2σ		P8 (0.5)
Greenland	P8	lognormal, 2σ	$V(t)/V(0)$, (9% | $\Delta T=1$) $V'(t)/V'(0)$ (8.5% | $\Delta T=1$)	P7 (0.5)
Antarctic Precip Adjustment for Area	P9	lognormal, 2σ	1/3, 2/3	none
NOTE: V(t) is the saturation vapor pressure at a particular time. *V'(t) is dV/dT at a particular time.*				
ICE SHEET AND ICE SHELF ASSUMPTIONS				
Ice Shelf Melt				
Sea ice Sensitivity to Global Temperature	P10	lognormal, 2σ	0.05, 0.2	$P10=e_{w/T}$
Sensitivity of Ross Ice Shelf Warm Intrusions	1+A1	lognormal, 2σ	1, 36	none
Ross Melt response to warm intrusion	A2	lognormal	0.25, 1.0	none
Probability of Undiluted CDW Under Ross	C3	binomial	$0.05\Delta T_{CDW}$ up to max of 0.25	none
Sensitivity of Weddell Sea to T_{cdw}	A3	fixed	1.0	none
Ronne/Filchner Basal Melt from Weddell warming	A4	lognormal 2σ	1.91, 3.33	none
Threshold for Melt Only Model	A7	Right Triangular	$p(x) = 2x$ $F(x) = x^2$	none
Ice Stream Model				
Initial Velocity of Ice Stream B	V_o	lognormal, 2σ	100, 300 m/yr	none
Upstream length, Shelf Backpressure	L	lognormal, 2σ	100, 300 km	none
Calving	C2	Trinomial Fixed Calving Reference Calving Enhanced Calving	 P(C2=2) = .7 P(C2=0) = .3 P(C2=1) = 0	none

	Parameter Distribution		**Value of**	**Correlation with**
Parameter	*Name*	*Shape, Moments*	**Moments**	**Other Parameters**
Antarctic Ice Sheet Model Selection (AM1+...+AM7 = 100%)				
AM1, IPCC No Ice Sheet Response, Precipitation Only			10	
AM2, Basal Melt Only			20	
Thomas Ice Stream--Extrapolation Options				
AM3, Continent Wide			5	
AM4, Only to Streams that Flow through Shelves			10	
AM5, Ratio of Ice Discharge to Melting			10	
AM6, Ice Stream Specific Response			25	
AM7, Oerlemans Model—Linearization			20	
Greenland				
Zero Ablation Line Response to ΔT	G1	lognormal, σ	111.1, 186.3 m/°C	none
Calving Response to Ablation	G2	normal, 2σ	0, 1.14	none
Response time due to Refreezing	G3	lognormal, σ	12.5, 50 years	none
Mountain Glaciers				
Response Time	t	lognormal, σ	10, 30 years	none
Historic Contribution				
Oerlemans	M1	normal, σ	0.515, 1.885	none
Meier	M2	normal, σ	.2, 4.4	none
P(Meier Estimate)	C4	binomial	P(C4=1)=0.5	none

TABLE 2. CUMULATIVE PROBABILITY DISTRIBUTION, TOTAL SEA LEVEL RISE (CM)

Cumulative		**Year**	
Probability (%)	*2030*	*2100*	*2200*
1	4.1	15	28
5	6.3	22	43
10	7.8	28	55
20	9.7	35	72
30	12	40	84
40	13	46	100
50	15	52	112
60	16	58	128
70	18	65	148
80	20	73	180
90	23	88	228
95	26	101	280
99	31	131	400

TABLE 3. SUMMARY OF RESULTS FOR SELECTED YEARS AND PERCENTILES

Scenario	Thermal Expansion	Mountain Glaciers	Greenland	Antarctica	Total
1 percent					
2030	2.8	-2.4	0.15	-1.4	4.1
2100	8.7	-7.1	1.4	-5.5	15
2200	16	-10.4	4.0	-15	28
10 percent					
2030	4.8	1.5	0.32	-0.85	7.8
2100	16.0	4.4	2.8	-2.7	27.5
2200	30	6.8	10	-2.0	55
Median					
2030	8.4	5.5	0.72	-0.15	14.7
2100	30.0	14.0	6.9	-1.0	51.5
2200	61	19.2	26	3.0	112
90 percent					
2030	13.3	10.9	1.47	0.8	23.5
2100	52.0	21.7	16.9	2.9	88
2200	115	26.8	76	25	228
99 percent					
2030	17.9	13.1	4.17	2.1	31
2100	78.2	25.7	34.4	16	131
2200	193	30.8	163	157.5	400

TABLE 4. COMPARISON BETWEEN IPCC (1990) AND THIS STUDY'S RESULTS FOR 2100

Scenario	Thermal Expansion	Mountain Glaciers	Greenland	Antarctica	Total
IPCC/low	25.8	7.8	2.9	-7.6	29.0
1 percent	8.7	7.1	1.4	-5.5	15.0
10 percent	6.0	4.4	2.8	-2.7	27.5
IPCC/best	38.7	18.5	11.6	-5.36	64.0
Wigley/best					48.0
Median	30.0	14.0	6.9	-1	51.5
IPCC/high	58.0	21.5	27.7	0.0	107.2
90 percent	52.0	21.7	16.9	2.9	88
99 percent	78.2	25.7	34.4	16	131

Note: The IPCC results cited here are somewhat different from those of IPCC 1990 because they are with respect to a 1990 base, rather than the IPCC's 1985 base. In addition, IPCC 1990 may reflect some rounding.

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History of Tropical Cyclones in the Caribbean: 1886–1986

Calvin R. Gray
National Meteorological Service
Kingston, Jamaica

Abstract

Records from 1886 to 1986 of hurricanes, tropical storms, and tropical depressions occurring in the Caribbean have been analyzed to determine their annual and monthly distributions. It has been found that the number of occurrences per year of hurricanes, tropical storms, and tropical depressions, taken separately, approaches Poisson distribution with +1.4356, 1.6436, and 0.8333, respectively. The monthly frequency distributions of the three events show that they are most likely to occur during the month of September, with probabilities of 34, 27, and 38 percent, respectively. Between the African coast and the Caribbean, the zones 10°-15°N and 15°-20°N were found to be the origin of 45 and 13 percent, respectively, of the hurricanes entering the Caribbean. During the 101-year period under review, there were 492 hurricanes in the Atlantic Ocean, Gulf of Mexico, and the Caribbean Sea, with 20 percent of them originating within the Caribbean Sea. These findings have practical value, particularly with respect to disaster prevention and preparedness, since the above events are disaster sources in all the Caribbean Islands.

Introduction

Tropical cyclones, reputedly the most destructive of nature's phenomena, are known in their mature form as hurricanes in the Atlantic, typhoons in the Western North Pacific, cyclones in the Bay of Bengal and the Arabian Sea, and Wily-Nily in the Australian region.

In the Caribbean, Gulf of Mexico, and Atlantic Ocean, a hurricane is defined as a storm of tropical origin with a cyclonic wind circulation of 75 MPH or more. With wind speeds of 39 to 74 MPH, the system is called a tropical storm, and if speeds are less than 39 MPH, it is called a tropical depression. The time of the year with a relatively high incidence of hurricanes is referred to as the "hurricane season." In the Atlantic, Caribbean, and Gulf of Mexico it is usually regarded as the period of June through November.

The damage caused by tropical cyclones, in particular hurricanes, comes from three principal sources: winds, torrential rainfall, and ocean waves and/or storm surge. For some structures, wind force is sufficient to cause destruction; however, the greatest threat from hurricane-force winds is their cargo of debris—a deadly barrage of flying missiles. The destruction of vegetation and agricultural products is often complete, especially on the smaller islands.

In the Caribbean, tropical depressions, tropical storms, and hurricanes often produce intense and prolonged rainfall, resulting in severe flooding. Frequently, loss of life, destruction of property and the havoc due to flooding far exceed the damage due to the hurricane-force winds.

The most destructive element of the hurricane and the greatest threat to human life is posed by the battering waves and the hurricane's storm surge.

Records of tropical cyclones for the Caribbean during the period 1886–1986 are being analyzed to identify a frequency distribution that would represent the occurrence of the events related to time, for the final purpose of disaster planning, prevention, and preparedness.

TROPICAL CYCLONES

Synoptic-scale disturbances of low latitudes can be classified in many ways—e.g., geographical location, geometrical form, and intensity. It is also convenient for the purpose of discussion to divide them into three broad groups based on their general appearance: vortices, wave-like perturbations, and linear systems.

Under the group classified as vortices, we find cyclones and the term tropical cyclone used in a general sense to denote any cyclonic vortex in the tropical troposphere.

Now, from the point of physical processes, one can distinguish two main classes of tropical cyclones: (1) those whose intensity is greatest near the surface, decreasing upward, and (2) those whose intensity is greatest in the upper troposphere, decreasing downward. The former are known as warm-core and the latter cold-core systems, and each class exhibits a wide range of sizes and intensities.

The low-level cyclones range in intensity from barely detectable to the most severe of hurricanes. They originate mostly from intensification of synoptic disturbances in the equatorial trough, but they may also form as a result of the transformation of previously cold-core systems.

The high-level cyclones also vary in intensity, to an extent that they are sometimes subdivided into different types. Some appear to be of mid-latitude origin, their formation due to differential subsidence of cold air of high-latitude origin. Others have been shown to form entirely in the upper troposphere of low latitudes. They frequently do not extend as vortex below 20,000 to 25,000 feet; instead a weak wave-like perturbation of the low tropospheric easterlies will be found beneath them. However, it is possible for them to acquire a warm-core structure, and they may occasionally develop into hurricanes.

In general, the following are considered necessary for formation of tropical cyclones:

- A preexisting area of disturbed weather.
- Sufficiently large sea areas with water temperature so high (<26 C) that moist air lifted from the lowest layers of the atmosphere remains considerably warmer than the surroundings.
- Weak vertical wind shear.
- A coriolis parameter larger than a certain critical value.

The mature tropical cyclone—a hurricane—can be divided in to four parts:

- An outer region, with inward increasing cyclonic wind speeds.
- A belt, in the inner portion of which the wind reaches at least 75 MPH.
- A more or less circular inner rain region, with very heavy rain and squalls.
- The "eye," a region of very light or calm wind where the lowest central pressure of the system is found.

FREQUENCY OF TROPICAL CYCLONES

Table 1 shows tropical cyclones in the Caribbean during the period 1886 to 1986, while the graphs of their annual frequencies are shown in Figures 1 to 3. The monthly and relative frequencies are given in Tables 2 and 3 with the corresponding graphs in Figures 4 to 6.

FIGURE 1. ANNUAL FREQUENCY OF HURRICANES IN THE CARIBBEAN (1886-1986)

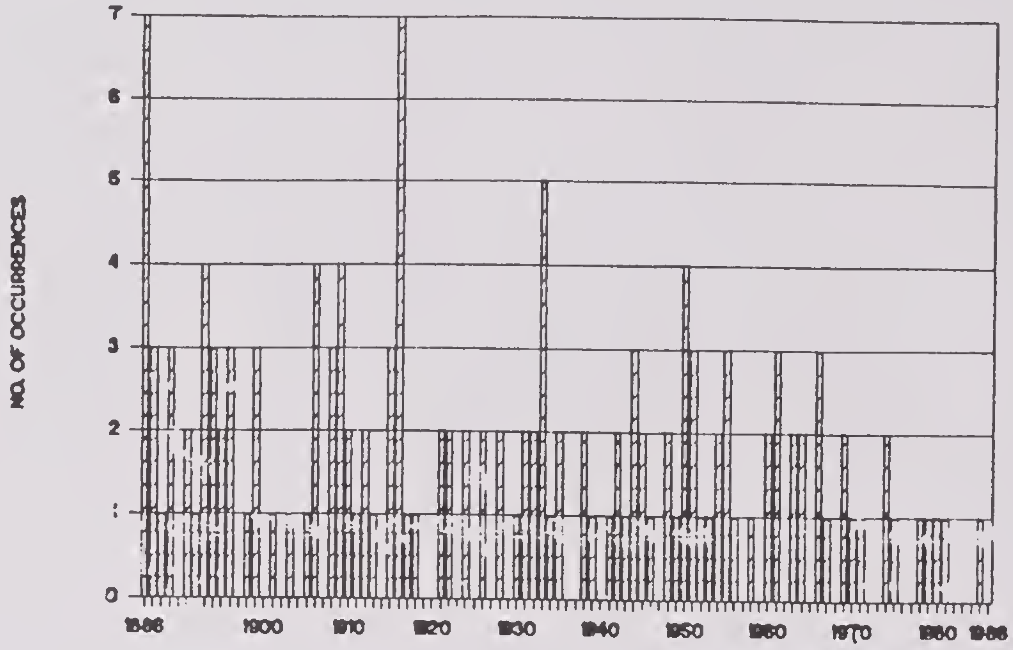


FIGURE 2. ANNUAL FREQUENCY OF TROPICAL STORMS IN THE CARIBBEAN (1886-1986)

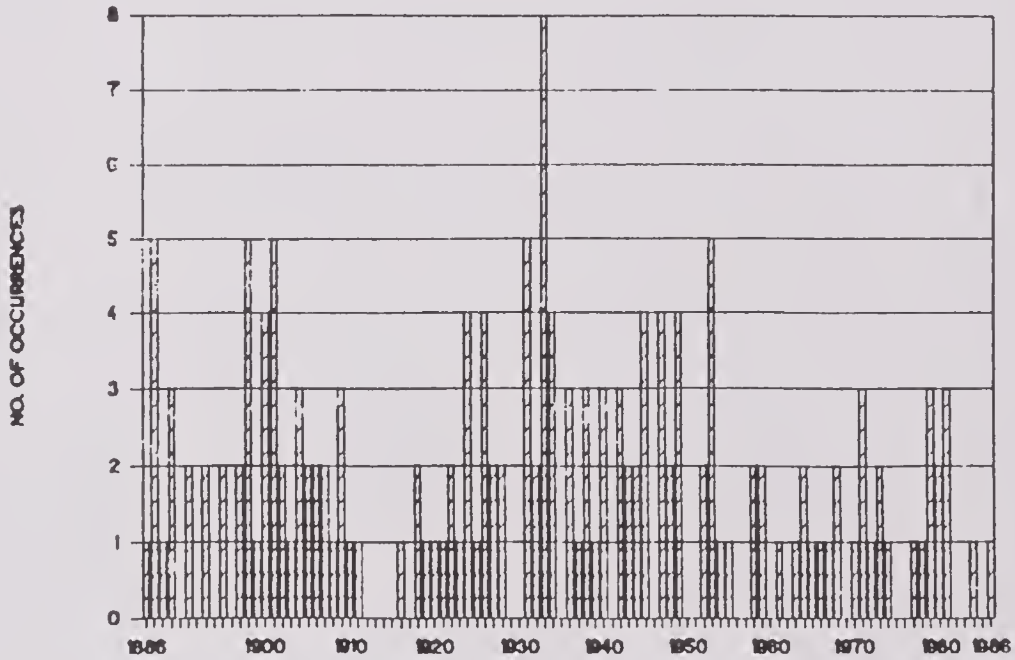


FIGURE 3. ANNUAL FREQUENCY OF TROPICAL DEPRESSIONS IN THE CARIBBEAN (1886-1986)

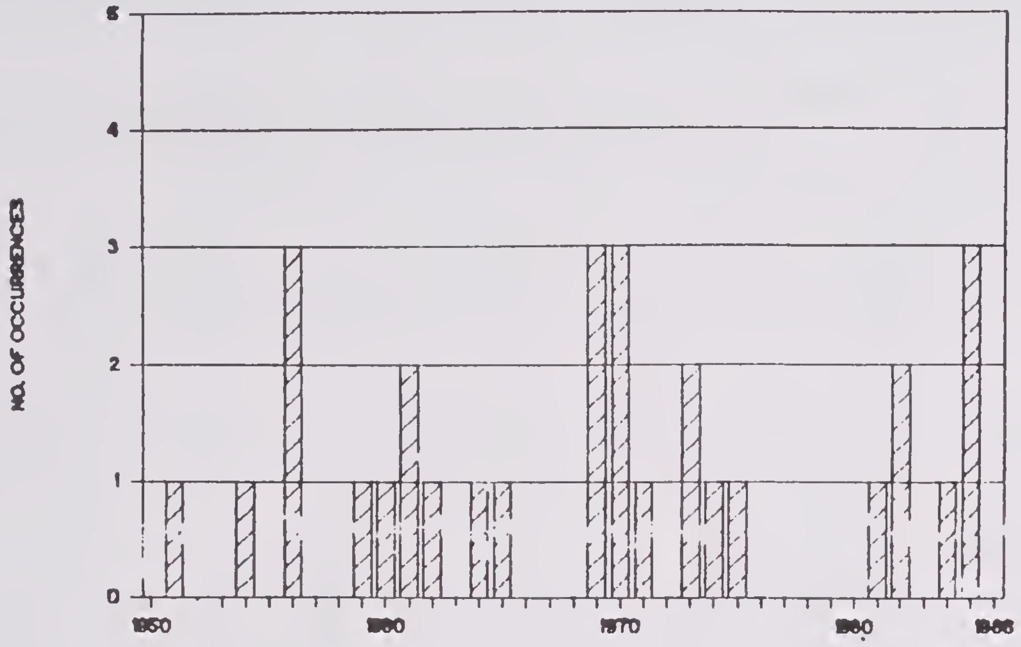


FIGURE 4. MONTHLY FREQUENCY OF HURRICANES IN THE CARIBBEAN (1886-1986)

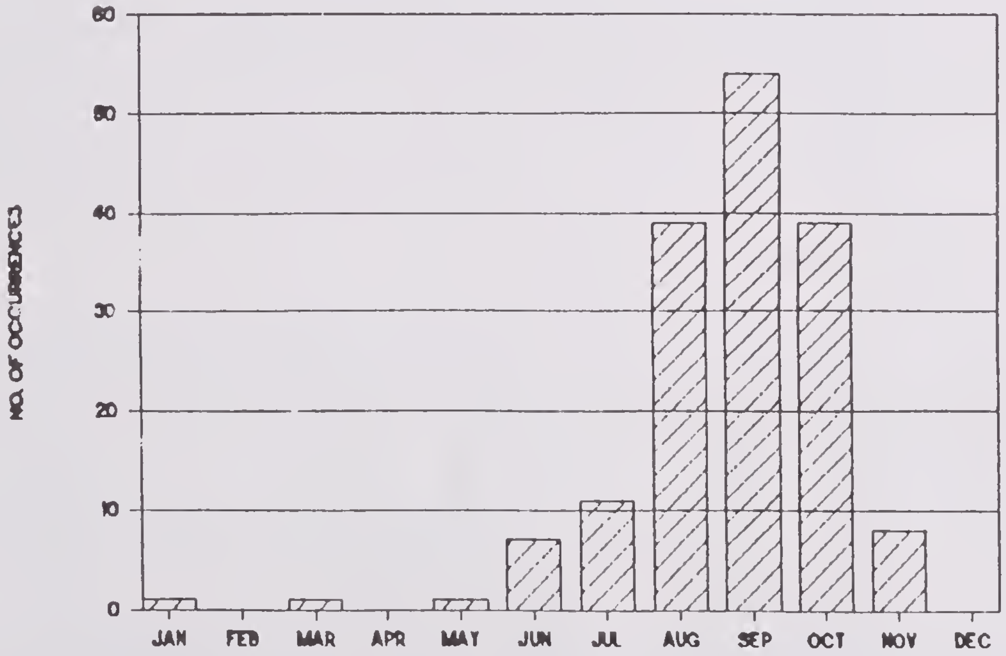


FIGURE 5. MONTHLY FREQUENCY OF TROPICAL STORMS IN THE CARIBBEAN (1886-1986)

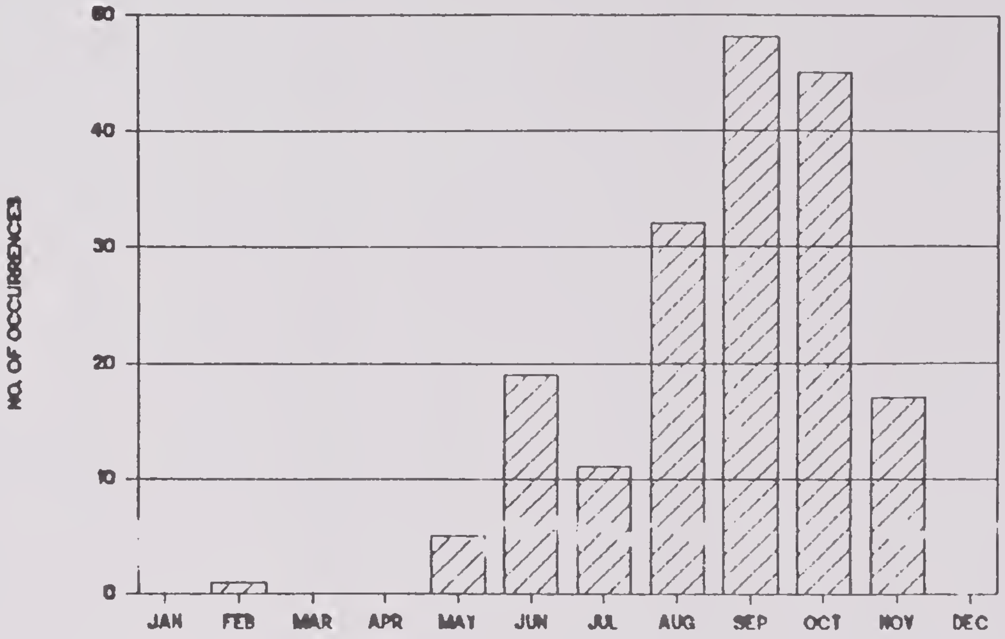


FIGURE 6. MONTHLY FREQUENCY OF TROPICAL DEPRESSIONS IN THE CARIBBEAN (1951-1986)

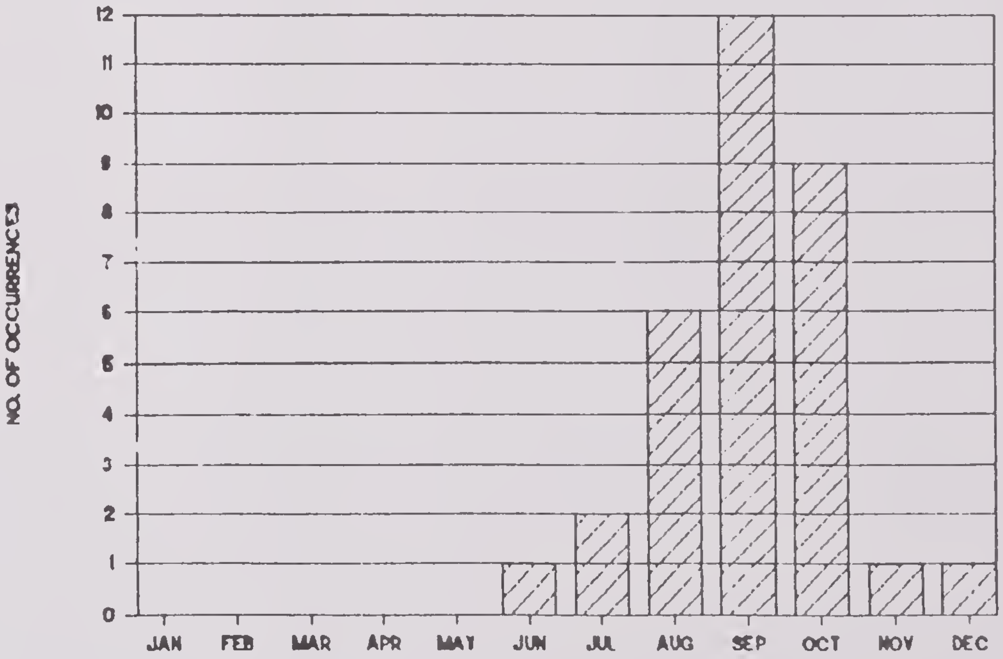


TABLE 1. TROPICAL CYCLONES IN THE CARIBBEAN: 1886 TO 1986

Year	Tropical Hurricane	Tropical Storm	Depression
1886	7	1	--
1887	3	5	--
1888	1	1	--
1889	3	3	--
1890	0	0	--
1891	2	2	--
1892	1	0	--
1893	4	2	--
1894	3	0	--
1895	2	2	--
1896	3	0	--
1897	0	2	--
1898	1	5	--
1899	3	1	--
1900	0	4	--
1901	1	5	--
1902	0	2	--
1903	1	1	--
1904	0	3	--
1905	1	2	--
1906	4	2	--
1907	0	2	--
1908	3	1	--
1909	4	3	--
1910	2	1	--
1911	1	1	--
1912	2	0	--
1913	1	0	--
1914	0	0	--
1915	3	0	--
1916	7	1	--
1917	1	0	--
1918	1	2	--
1919	0	1	--
1920	0	1	--
1921	2	1	--
1922	2	2	--
1923	0	1	--
1924	2	4	--
1925	0	1	--
1926	2	4	--
1927	0	2	--
1928	2	2	--
1929	0	0	--
1930	1	0	--
1931	2	5	--
1932	2	2	--
1933	5	8	--
1934	1	4	--
1935	2	0	--

TABLE 1 (CONT'D) TROPICAL CYCLONES IN THE CARIBBEAN: 1886 TO 1986

Year	Hurricane	Tropical Storm	Tropical Depression
1936	0	3	--
1937	0	1	--
1938	2	3	--
1939	1	1	--
1940	0	3	--
1941	1	0	--
1942	2	3	--
1943	1	2	--
1944	3	2	--
1945	2	4	--
1946	1	0	--
1947	0	4	--
1948	2	2	--
1949	1	4	--
1950	4	0	--
1951	3	0	1
1952	1	2	0
1953	1	5	0
1954	1	1	1
1955	4	1	0
1956	1	0	3
1957	0	0	0
1958	1	2	0
1959	0	2	1
1960	2	0	1
1961	3	1	2
1962	0	0	1
1963	2	1	0
1964	2	2	1
1965	0	1	1
1966	3	1	0
1967	1	1	0
1968	0	2	0
1969	2	0	3
1970	1	1	3
1971	1	3	1
1972	0	1	0
1973	0	2	2
1974	2	1	1
1975	1	0	1
1976	0	0	0
1977	0	1	0
1978	1	1	0
1979	1	3	0
1980	1	2	0
1981	1	3	1
1982	0	0	2
1983	0	0	0
1984	0	1	1
1985	1	0	3
1986	0	1	0

TABLE 2. MONTHLY RELATIVE FREQUENCY OF TROPICAL CYCLONES IN THE CARIBBEAN: 1886 TO 1986

	HURRICANES		TROPICAL STORMS		TROPICAL DEPRESSIONS	
MONTH	*Total*	*Relative Frequency*	*Total*	*Relative Frequency*	*Total*	*Relative Frequency*
Jan.	1	0.006	0	0.000	0	0.000
Feb.	0	0.000	0	0.000	0	0.000
Mar.	1	0.006	0	0.000	0	0.000
Apr.	0	0.000	0	0.000	0	0.000
May	1	0.006	5	0.028	0	0.000
June	7	0.043	19	0.107	1	0.031
July	11	0.068	11	0.062	2	0.063
Aug.	39	0.242	32	0.180	6	0.188
Sept.	54	0.335	48	0.270	12	0.375
Oct.	39	0.242	45	0.253	9	0.281
Nov.	8	0.050	17	0.096	1	0.031
Dec.	0	0.000	0	0.000	1	0.031
TOTAL	**161**	**1.000**	**178**	**1.000**	**32**	**1.000**

TABLE 3. RELATIVE FREQUENCY OF TROPICAL CYCLONES IN THE CARIBBEAN: 1886 TO 1986

	HURRICANES		TROPICAL STORMS		TROPICAL DEPRESSIONS	
NO. OF EVENTS	*No. of Years*	*Relative Frequency*	*No. of Years*	*Relative Frequency*	*No. of Years*	*Relative Frequency*
0	30	0.297	26	0.257	17	0.472
1	31	0.307	29	0.287	12	0.333
2	21	0.208	23	0.228	3	0.083
3	11	0.109	10	0.099	4	0.111
4	5	0.050	7	0.069	0	0.000
5	1	0.010	5	0.050	0	0.000
6	0	0.000	0	0.000	0	0.000
7	2	0.020	0	0.000	0	0.000
8	0	0.000	1	0.010	0	0.000
TOTAL	**101**	**1.000**	**101**	**1.000**	**36**	**1.000**

The tables show that in any given year in the Caribbean, there are respective probabilities of 30, 26, and 47 percent that there will be no hurricanes, tropical storms, or tropical depressions. Further, hurricanes, tropical storms and tropical depressions are most likely to occur in September, with probabilities of 34, 27, and 38 percent, respectively. During the 101-year period, April was the only month during which a tropical cyclone had never been observed in the Caribbean.

ORIGIN, TRACK, AND DECADAL TREND

Tropical cyclones that affected the Caribbean from 1886 to1986 formed either in the North Atlantic or within the Caribbean Sea. No systems that formed in the Gulf of Mexico or the Pacific Ocean entered the Caribbean.

Table 4 shows that from 1886 to 1986, 492 hurricanes were observed in the Atlantic Ocean, Gulf of Mexico, and the Caribbean Sea. Of this number, 321 (65 percent) originated in the North Atlantic between 10°-2°°N and from within the Caribbean Sea. The area in the Atlantic Ocean between 10°-15°N was the origin of 133 hurricanes while, 97 and 91 were from within the Caribbean Sea and from 15°-20°N in the Atlantic, respectively.

TABLE 4. TROPICAL CYCLONES IN THE ATLANTIC OCEAN, GULF OF MEXICO AND THE CARIBBEAN SEA: 1886 TO 1986

	Hurricane	Tropical Storm	Tropical Depression
Caribbean, 1886-1890	14	10	--
Caribbean, 1891-1900	19	18	--
Caribbean, 1901-1910	16	22	--
Caribbean, 1911-1920	16	6	--
Caribbean, 1921-1930	11	17	--
Caribbean, 1931-1940	15	30	--
Caribbean, 1941-1950	17	21	--
Caribbean, 1951-1960	14	13	7
Caribbean, 1961-1970	14	10	11
Caribbean, 1971-1980	7	14	5
Caribbean, 1981-1986	2	5	7
Caribbean, 1886-1986	145	166	30*
Caribbean, origin Caribbean Sea	97	176	--
Enter Caribbean, origin 15-20N	19	32	--
Enter Caribbean, origin 10-15N	65	107	--
Outside Caribbean, 15-20N	91	120	--
Outside Caribbean, 10-15N	133	182	--
Curve NORTH of 20N, origin 15-20N	91	126	--
Curve NORTH of 20N, origin 10-15N	108	140	--
Atlantic, Gulf of Mexico & Caribbean	492	232	--

---

*For the period 1951–1986

Of the 145 hurricanes in the Caribbean, 45 percent originated from 10°-15°N with 13 percent from 15°-20°N.

Four systems formed north of 20°N in the Atlantic and entered the Caribbean:

- Hurricane "Lili," which developed from a subtropical storm near the 35°N60°W on December 12, 1984, tracked south, completed a circle, intensified to a hurricane, and headed SSW into the Caribbean where it dissipated.
- Hurricane "Alice," December 30, 1954–January 5, 1955, started as a depression near 22.5°N50°W, intensified to a hurricane, headed SSW into the Caribbean Sea, and dissipated about 12°N63°W.

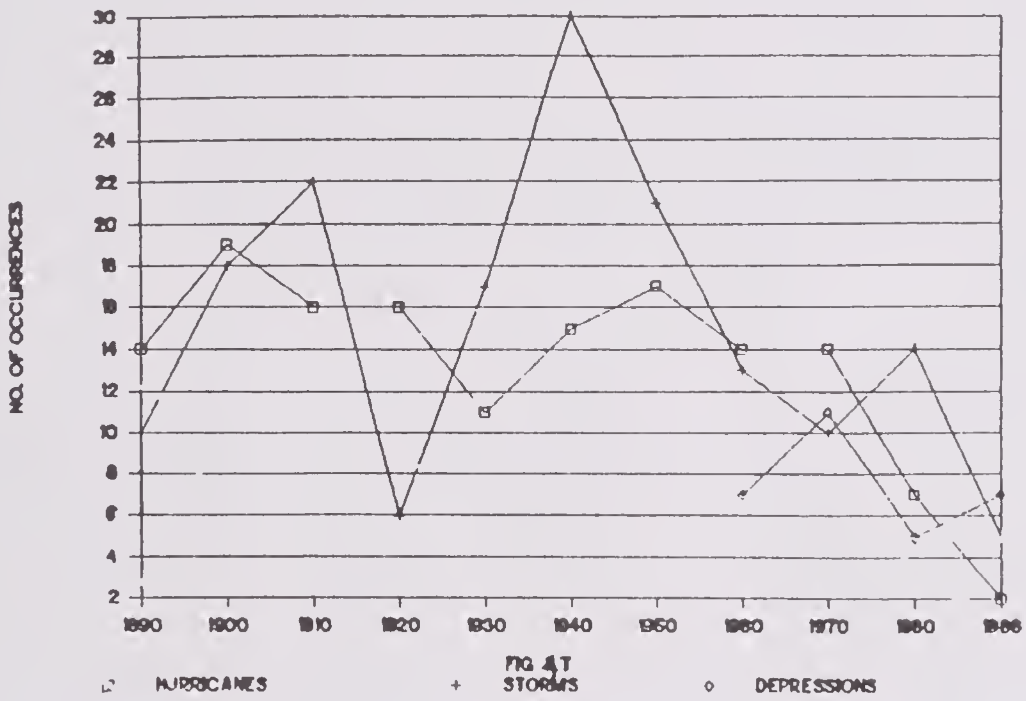
- On November 20-28, 1994, a depression formed about 21°N57°W intensified to a hurricane, headed north to about 32°N65°W, recurved and headed SSW, moved across the Dominican Republic into the Caribbean Sea, and dissipated at about 17.5°N71°W.

- On March 6-9, 1908, a depression formed near 25°N60°W, headed SSW, intensified to a hurricane, moved across the Virgin Islands, and dissipated near 13°N65°W.

Of the 91 hurricanes that originated 15°-20°N in the Atlantic from 1886 to 1986, all ended up above 20°N, while 81 percent of the 133 that originated 10°-15°N also ended up above 20°N. This supports a general westerly track. Also, seasonal differences in the locations of tropical cyclone formation and the environmental circulations can lead to differences in track. For example, the Atlantic tropical cyclones of June tend to form in the western Caribbean or Gulf of Mexico, with a subsequent track to the north.

Figure 7 shows that the most active decades with respect to hurricanes, tropical storms, and tropical depressions ended in the years 1900, 1940, and 1970, with 19, 30, and 11 cyclones, respectively. The least active decades ended in the years 1920, 1960, and 1980, with 7, 6 and 5 cyclones, respectively.

FIGURE 7. DECADE TOTALS OF TROPICAL CYCLONES IN THE CARIBBEAN (1886-1986)



POISSON DISTRIBUTION

The Poisson distribution has been applied to tropical cyclones, as they satisfy the following postulates or the model:

- The number of occurrences of tropical cyclones is independent from one time unit to another.

- The expected value of the variable is proportional to the size of the time limit.
- The probability of more than one occurrence of a tropical cyclone in a very small time unit is negligible in comparison with the probability of a single occurrence. Therefore, it can be neglected.

The Poisson model is completely defined by its mean number of occurrences per unit time. The probability mass function is given by:

$$P(X:) = (/X!).e \quad ; \quad X= 0,1,2,3,.....$$

Thus, considering the one-year time unit and that in the period 1886–1986—a period of 101 years—145 hurricanes, and 166 tropical storms were observed, and given that 30 tropical depressions were also observed in the 36-year period from 1951 to 1986, we have the Poisson distribution parameters = 1.436, =1.6436 and =0.8333.

Table 5 shows the observed and expected cumulative frequencies with the graphs of the individual events in Figures 8–10.

TABLE 5. OBSERVED AND EXPECTED CUMULATIVE DISTRIBUTION OF TROPICAL CYCLONES IN THE CARIBBEAN: 1886 TO 1986

	HURRICANE			**TROPICAL STORM**			**TROPICAL DEPRESSION**		
# OF EVENTS/ YEAR	*Obs.*	*Exp.*	*Absolute Diff.*	*Obs.*	*Exp.*	*Absolute Diff.*	*Obs.*	*Exp.*	*Absolute Diff.*
0	0.297	0.238	0.059	0.257	0.193	0.064	0.472	0.435	0.037
1	0.604	0.580	0.024	0.545	0.511	0.034	0.806	0.797	0.009
2	0.812	0.825	0.013	0.772	0.772	0.000	0.889	0.948	0.059
3	0.921	0.942	0.021	0.871	0.915	0.044	1.000	0.990	0.010
4	0.971	0.984	0.013	0.941	0.974	0.033			
5	0.981	0.996	0.015	0.990	0.993	0.003			
6	0.981	0.999	0.018	0.990	0.998	0.008			
7	1.000	1.000	0.000	0.990	0.999	0.009			
8				1.000	1.000	0.000			

The Kolmogorov-Smirnov test was used for the goodness of fit between the observed and the assumed Poisson distribution, see Table 6.

We observe in all three cases that the maximum absolute deviation between the observed and theoretical value is much less than the critical values of the Kolmogorov-Smirnov test. Therefore, we accept the hypothesis that the observed distribution is Poisson at a 0.05 significance level.

FIGURE 8. OBSERVED AND EXPECTED FREQUENCY OF HURRICANES IN THE CARIBBEAN (1886-1986)

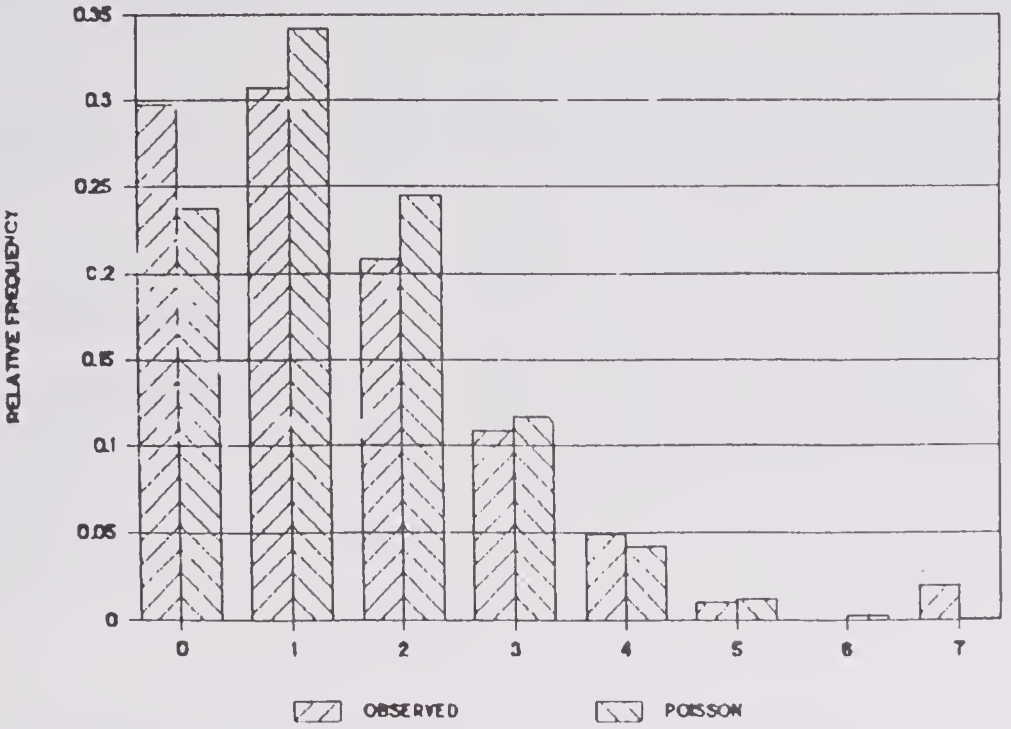


FIGURE 9. OBSERVED AND EXPECTED FREQUENCY OF TROPICAL DEPRESSIONS IN THE CARIBBEAN (1951-1986)

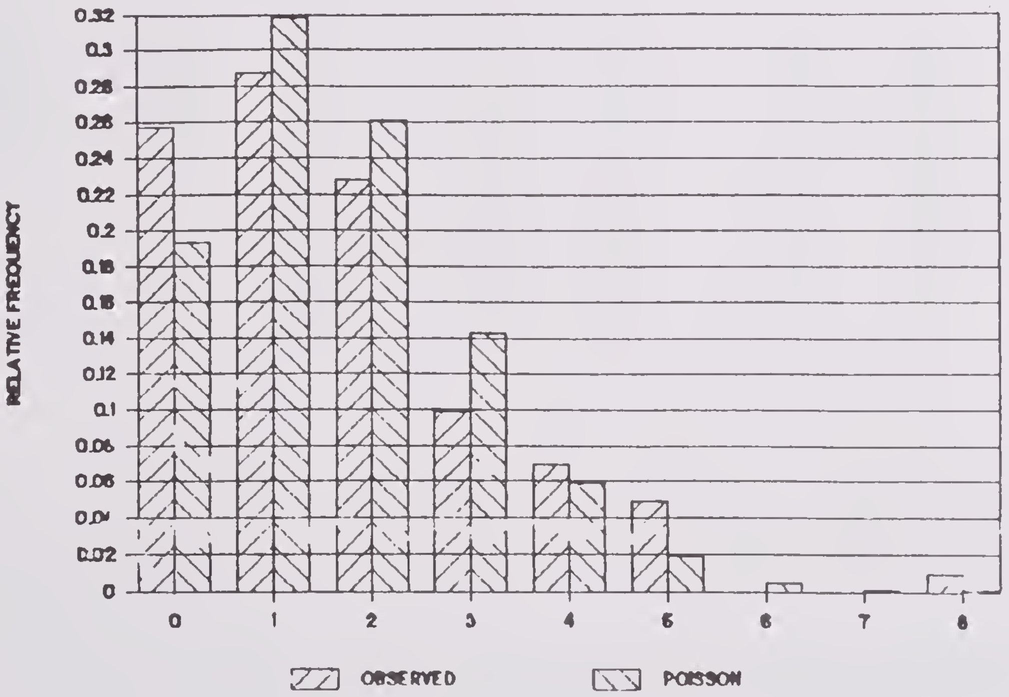


FIGURE 10. OBSERVED AND EXPECTED FREQUENCY OF TROPICAL DEPRESSIONS IN THE CARIBBEAN (1951-1986)

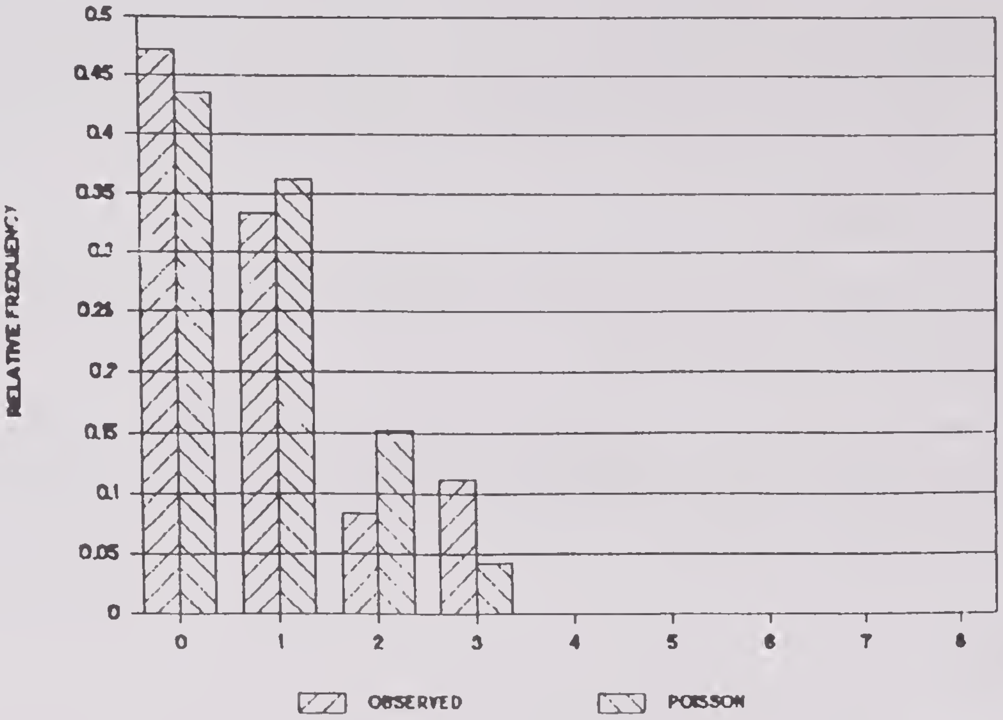


TABLE 6. KOLMOGOROV-SMIRNOV TEST OF GOODNESS OF FIT

	Hurricane	Tropical Storm	Tropical Depression
Maximum deviation between observed and expected value	0.059	0.064	0.059
Critical value in the K-S test at 0.05 level	0.135	0.135	0.227
Conclusion	Reject Ho	Reject Ho	Reject Ho

Ho: Observed distribution is not Poisson, that is, the maximum absolute deviation is greater than the critical value.

Hl: Observed distribution is Poisson, that is, the maximum absolute deviation is less than or equal to the critical value.

CONCLUSION/RECOMMENDATIONS

It is possible to adjust the number of annual occurrences of tropical cyclones to the Poisson probability distribution function. Using this technique, it was found that one hurricane, one tropical storm, or one tropical depression can be expected in the Caribbean once every three years.

These results are very helpful for disaster planning, prevention, and preparedness. Hence—as a first approximation—this information will benefit all regional disaster prevention and preparedness agencies to gain support, understanding, and cooperation from local and international agencies in their activities relating to:

- Delimitation of flood-prone areas.
- Establishment of severe weather warning systems.
- Flood control systems.
- Education and training of the population so that the people are aware of risks of disaster and their prevention requirements.

The information should be updated periodically, especially in the case of tropical depressions, where only 36 years of data were available, since tropical depressions have caused extensive flooding in many Caribbean islands.

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Personal communication with Arthur C. Pike, Research Meteorologist, U.S. Dept. of Commerce, National Weather Service, Coral Gables, Florida, USA.

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